Vol. 2

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MACHINING DATA HANDBOOK

3rd EDITION

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MACHINING DATA HANDBOOK

The data contained in this publication have been derived from many sources including tests conducted under conditions which may or may not exist where such data are used. Changes in conditions of processing (machining, fabrication, heat treatment, etc.) and differences in material properties from those described herein may make some or all of the data used inappropriate under the circumstances. Users of the enclosed information are thus cautioned that the information contained herein should be used only as a guide where the user judges it to be appropriate. Metcut Research Associates Inc., contractor to the United States Government, disclaims any and all responsibility for use of the information contained herein by readers and users of this publication.

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(15) DLA900-77-C-2197

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MACHINING DATA HANDBOOK

3rd Edition

AD926914

VOLUME TWO

Compiled by the
Technical Staff
of the
Machinability Data Center
A DoD Information Analysis Center
Sponsored by the
Army Materials and Mechanics Research Center

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Scope

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MDC has a data file of over thirty-two thousand selected documents pertaining to material removal technology. This data file is supported by a computer system for retrieval of information based upon the specific material (with definite chemical, physical, and mechanical properties) and the specific material removal operation being used. Computerized search techniques are employed utilizing a combination of search parameters to produce source data. Information retrieval can be refined to the extent necessary to satisfy the requirements of a specific inquiry by controlling the input search parameters.

For information: Contact the Machinability Data Center, 3980 Rosslyn Drive, Cincinnati, OH 45209. Telephone: (513) 271-9510. TWX: 810-461-2840.

ISBN 0-936974-00-1 (Set)
ISBN 0-936974-02-8 (Volume 2)
Library of Congress Catalog Card Number: 80-81480

Metcut Research Associates Inc.
3980 Rosslyn Drive
Cincinnati, OH 45209

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First Edition published 1966. Second Edition 1972. Third Edition 1980

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Printed in the United States of America

Typeset in Helvetica and Bookman by Dayton Typographic Service Inc., Dayton, Ohio
Graphics by Repro Art Service Inc., Cincinnati, Ohio
Printed and bound by The Johnson & Hardin Co., Cincinnati, Ohio

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1. FREE MACHINING CARBON STEELS, WROUGHT							
Low Carbon Resulfurized							
1116	100 to 150	Hot Rolled or Annealed	1—2	2	.060	220	M2 M7
1117			3—10	1	060	230	
1118			11—19	1	.060	240	
1119			20—48	1	.050	250	
1211			48 & Finer	1	.030	280	
1212			25—13	2	1.50	67	S4, S2
			12—2.5	1	1.50	70	
			2—1.5	1	1.50	73	
			1—.5	1	1.25	76	
			.5 & Finer	1	.75	85	
	150 to 200	Cold Drawn	1—2	2	.060	230	M2, M7
			3—10	1	.060	240	
			11—19	1	060	265	
			20—48	1	050	275	
			48 & Finer	1	.030	300	
			25—13	2	1.50	70	S4, S2
			12—2.5	1	1.50	73	
			2—1.5	1	1.50	81	
			1—.5	1	1.25	84	
			.5 & Finer	1	.75	90	
Low Carbon Resulfurized							
1213	100 to 150	Hot Rolled or Annealed	1—2	2	.060	240	M2, M7
1215			3—10	1	.060	250	
			11—19	1	060	265	
			20—48	1	.050	275	
			48 & Finer	1	.030	300	
			25—13	2	1.50	73	S4, S2
			12—2.5	1	1.50	76	
			2—1.5	1	1.50	81	
			1—.5	1	1.25	84	
			.5 & Finer	1	.75	90	
	150 to 200	Cold Drawn	1—2	2	.060	250	M2, M7
			3—10	1	060	270	
			11—19	1	060	285	
			20—48	1	050	295	
			48 & Finer	1	.030	330	
			25—13	2	1.50	76	S4, S2
			12—2.5	1	1.50	82	
			2—1.5	1	1.50	87	
			1—.5	1	1.25	90	
			.5 & Finer	1	.75	100	
Low Carbon Resulfurized							
1108	100 to 150	Hot Rolled or Annealed	1—2	2	.060	190	M2, M7
1109			3—10	1	.060	205	
1110			11—19	1	.060	220	
1115			20—48	1	.050	240	
			48 & Finer	1	.030	260	
			25—13	2	1.50	58	S4, S2
			12—2.5	1	1.50	62	
			2—1.5	1	1.50	67	
			1—.5	1	1.25	73	
			.5 & Finer	1	.75	79	
	150 to 200	Cold Drawn	1—2	2	.060	200	M2, M7
			3—10	1	.060	215	
			11—19	1	.060	230	
			20—48	1	.050	250	
			48 & Finer	1	.030	270	
			25—13	2	1.50	60	S4, S2
			12—2.5	1	1.50	66	
			2—1.5	1	1.50	70	
			1—.5	1	1.25	76	
			.5 & Finer	1	.75	82	

For hobbing Class 9 (per AGMA 390 03) or better gears, it may be necessary to reduce speeds and feeds by 50% and/or take 2 cuts. To meet finish requirements it may be necessary to try both conventional and climb cutting

See section 16 for Cutting Fluid Recommendations.

*Feeds are based on the largest standard recommended hob diameter. When using a smaller hob diameter, the Feed must be reduced proportionally.

7.1 Gear Hobbing

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	NUMBER OF CUTS	FEED* PER REVOLUTION OF WORKPIECE in / mm	HOB SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
1. FREE MACHINING CARBON STEELS, WROUGHT (cont.) **Medium Carbon Resulfurized** 1132 1144 1137 1145 1139 1146 1140 1151 1141	175 to 225	Hot Rolled, Normalized, Annealed or Cold Drawn	1—2	2	.060	170	M2, M7
			3—10	1	.060	180	
			11—19	1	.060	190	
			20—48	1	.050	200	
			48 & Finer	1	.030	220	
			25—10	2	1.50	52	S4, S2
			12—2.5	1	1.50	55	
			2—1.5	1	1.50	58	
			1—.5	1	1.25	60	
			.5 & Finer	1	.75	67	
	275 to 325	Quenched and Tempered	1—2	2	.060	120	M2, M7
			3—10	1	.060	140	
			11—19	1	.060	145	
			20—48	1	.050	150	
			48 & Finer	1	.030	165	
			25—13	2	1.50	37	S4, S2
			12—2.5	1	1.50	43	
			2—1.5	1	1.50	44	
			1—.5	1	1.25	46	
			.5 & Finer	1	.75	50	
	325 to 375	Quenched and Tempered	1—2	2	.060	70	M3, M42
			3—10	1	.060	90	
			11—19	1	.060	110	
			20—48	1	.050	120	
			48 & Finer	1	.030	130	
			25—13	2	1.50	27	S5, S11
			12—2.5	1	1.50	32	
			2—1.5	1	1.50	34	
			1—.5	1	1.25	37	
			.5 & Finer	1	.75	40	
Low Carbon Leaded 10L18 11L17	100 to 150	Hot Rolled, Normalized, Annealed or Cold Drawn	1—2	2	.065	230	M2, M7
			3—10	1	.065	250	
			11—19	1	.060	270	
			20—48	1	.050	290	
			48 & Finer	1	.030	300	
			25—13	2	1.50	70	S4, S2
			12—2.5	1	1.50	76	
			2—1.5	1	1.50	82	
			1—.5	1	1.25	86	
			.5 & Finer	1	.75	90	
	150 to 200	Hot Rolled, Normalized, Annealed or Cold Drawn	1—2	2	.065	190	M2, M7
			3—10	1	.065	220	
			11—19	1	.060	250	
			20—48	1	050	270	
			48 & Finer	1	.030	280	
			25—13	2	1.50	60	S4, S2
			12—2.5	1	1.50	67	
			2—1.5	1	1.50	76	
			1—.5	1	1.25	82	
			.5 & Finer	1	.75	86	
	200 to 250	Hot Rolled, Normalized, Annealed or Cold Drawn	1—2	2	.060	140	M2, M7
			3—10	1	.050	180	
			11—19	1	.050	200	
			20—48	1	.050	225	
			48 & Finer	1	.030	250	
			25—13	2	1.50	50	S4, S2
			12—2.5	1	1.50	55	
			2—1.5	1	1.50	58	
			1—.5	1	1.25	60	
			.5 & Finer	1	.75	67	

For hobbing Class 9 (per AGMA 390 03) or better gears, it may be necessary to reduce speeds and feeds by 50% and/or take 2 cuts. To meet finish requirements it may be necessary to try both conventional and climb cutting.

See section 16 for Cutting Fluid Recommendations.

*Feeds are based on the largest standard recommended hob diameter. When using a smaller hob diameter, the Feed must be reduced proportionally.

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	NUMBER OF CUTS	FEED* PER REVOLUTION OF WORKPIECE in / mm	HOB SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
Low Carbon Leaded 12L13 12L14 12L15	100 to 150	Hot Rolled, Normalized, Annealed or Cold Drawn	1—2	2	.065	255	M2, M7
			3—10	1	.065	265	
			11—19	1	060	295	
			20—48	1	.050	305	
			48 & Finer	1	.030	340	
			25—13	2	1.65	76	S4, S2
			12—2.5	1	1.65	81	
			2—1.5	1	1.50	90	
			1—.5	1	1.25	95	
			.5 & Finer	1	.75	105	
	150 to 200	Hot Rolled, Normalized, Annealed or Cold Drawn	1—2	2	.065	210	M2, M7
			3—10	1	.065	240	
			11—19	1	060	275	
			20—48	1	.050	285	
			48 & Finer	1	.030	320	
			25—13	2	1.65	64	S4, S2
			12—2.5	1	1.65	73	
			2—1.5	1	1.50	84	
			1—.5	1	1.25	87	
			.5 & Finer	1	.75	100	
	200 to 250	Hot Rolled, Normalized, Annealed or Cold Drawn	1—2	2	.060	165	M2, M7
			3—10	1	.060	190	
			11—19	1	.060	225	
			20—48	1	050	240	
			48 & Finer	1	.030	275	
			25—13	2	1.50	50	S4, S2
			12—2.5	1	1.50	58	
			2—1.5	1	1.50	66	
			1—.5	1	1.25	73	
			.5 & Finer	1	.75	84	
Medium Carbon Leaded 10L45 10L50 11L37 11L41 11L44	125 to 175	Hot Rolled, Normalized, Annealed or Cold Drawn	1—2	2	.060	200	M2, M7
			3—10	1	.060	210	
			11—19	1	.060	225	
			20—48	1	.050	240	
			48 & Finer	1	.030	260	
			25—13	2	1.50	60	S4, S2
			12—2.5	1	1.50	64	
			2—1.5	1	1.50	69	
			1—.5	1	1.25	73	
			.5 & Finer	1	.75	79	
	175 to 225	Hot Rolled, Normalized, Annealed or Cold Drawn	1—2	2	.060	190	M2, M7
			3—10	1	060	200	
			11—19	1	.060	210	
			20—48	1	.050	225	
			48 & Finer	1	.030	240	
			25—13	2	1.50	50	S4, S2
			12—2.5	1	1.50	58	
			2—1.5	1	1.50	64	
			1—.5	1	1.25	69	
			.5 & Finer	1	.75	73	
	225 to 275	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	1—2	2	.060	180	M2, M7
			3—10	1	.060	190	
			11—19	1	.060	200	
			20—48	1	.050	205	
			48 & Finer	1	.030	220	
			25—13	2	1.50	56	S4, S2
			12—2.5	1	1.50	46	
			2—1.5	1	1.50	58	
			1—.5	1	1.25	66	
			.5 & Finer	1	.75	67	

For hobbing Class 9 (per AGMA 390.03) or better gears, it may be necessary to reduce speeds and feeds by 50% and/or take 2 cuts. To meet finish requirements it may be necessary to try both conventional and climb cutting.

See section 16 for Cutting Fluid Recommendations.

*Feeds are based on the largest standard recommended hob diameter. When using a smaller hob diameter, the Feed must be reduced proportionally.

7.1 Gear Hobbing

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	NUMBER OF CUTS	FEED* PER REVOLUTION OF WORKPIECE in / mm	HOB SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
1. FREE MACHINING CARBON STEELS, WROUGHT (cont.) Medium Carbon Leaded (cont.) (materials listed on preceding page)	275 to 325	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	1—2	2	060	130	M2, M7
			3—10	1	.060	140	
			11—19	1	.060	150	
			20—48	1	.045	160	
			48 & Finer	1	.030	175	
			25—13	2	.150	30	
			12—2.5	1	.150	43	
			2—1.5	1	.150	48	
			1—.5	1	.115	40	
			.5 & Finer	1	.75	53	
	325 to 375	Quenched and Tempered	1—2	2	.060	80	M3, M42
			3—10	1	045	90	
			11—19	1	.045	105	
			20—48	1	025	120	
			48 & Finer	1	.025	140	
			25—13	2	.150	24	
			12—2.5	1	.115	27	
			2—1.5	1	.115	32	
			1—.5	1	.85	34	
			.5 & Finer	1	.65	43	
2. CARBON STEELS, WROUGHT Low Carbon 1005 1019, 1006 1020, 1008 1021, 1009 1022, 1010 1023, 1011 1025, 1012 1026, 1013 1029, 1015 1513, 1016 1518, 1017 1522, 1018	85 to 125	Hot Rolled, Normalized, Annealed or Cold Drawn	1—2	2	.070	205	M2, M7
			3—10	1	.070	245	
			11—19	1	.060	265	
			20—48	1	.050	280	
			48 & Finer	1	.030	290	
			25—13	2	.150	45	
			12—2.5	1	.115	75	
			2—1.5	1	.115	81	
			1—.5	1	.85	85	
			.5 & Finer	1	.65	95	
	125 to 175	Hot Rolled, Normalized, Annealed or Cold Drawn	1—2	2	070	175	M2, M7
			3—10	1	070	190	
			11—19	1	.060	200	
			20—48	1	.050	210	
			48 & Finer	1	.030	220	
			25—13	2	.150	35	
			12—2.5	1	.115	60	
			2—1.5	1	.115	65	
			1—.5	1	.85	65	
			.5 & Finer	1	.65	75	
	175 to 225	Hot Rolled, Normalized, Annealed or Cold Drawn	1—2	2	.070	145	M2, M7
			3—10	1	.070	170	
			11—19	1	.060	190	
			20—48	1	.050	200	
			48 & Finer	1	.030	210	
			25—13	2	.150	30	
			12—2.5	1	.115	45	
			2—1.5	1	.115	50	
			1—.5	1	.85	50	
			.5 & Finer	1	.65	60	
	225 to 275	Annealed or Cold Drawn	1—2	2	.060	120	M2, M7
			3—10	1	.060	160	
			11—19	1	.060	185	
			20—48	1	.050	195	
			48 & Finer	1	.030	200	
			25—13	2	.150	25	
			12—2.5	1	.115	40	
			2—1.5	1	.115	45	
			1—.5	1	.85	45	
			.5 & Finer	1	.65	55	

For hobbing Class 9 (per AGMA 390.03) or better gears, it may be necessary to reduce speeds and feeds by 50% and/or take 2 cuts. To meet finish requirements it may be necessary to try both conventional and climb cutting

See section 16 for Cutting Fluid Recommendations.

*Feeds are based on the largest standard recommended hob diameter. When using a smaller hob diameter, the Feed must be reduced proportionally.

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	NUMBER OF CUTS	FEED* PER REVOLUTION OF WORKPIECE in / mm	HOB SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
Medium Carbon 1030 1044 1526 1033 1045 1527 1035 1046 1536 1037 1049 1541 1038 1050 1547 1039 1053 1548 1040 1055 1551 1042 1524 1552 1043 1525	125 to 175	Hot Rolled, Normalized, Annealed or Cold Drawn	1—2	2	.070	165	M2, M7
			3—10	1	.070	175	
			11—19	1	.060	185	
			20—48	1	.050	200	
			48 & Finer	1	.030	210	
			[illegible]	2	1.80	50	S4, S2
			[illegible]	1	1.80	53	
			[illegible]	1	1.50	56	
			[illegible]	1	1.25	60	
			[illegible]	1	.75	64	
	175 to 225	Hot Rolled, Normalized, Annealed or Cold Drawn	1—2	2	.070	135	M2, M7
			3—10	1	.070	145	
			11—19	1	.060	165	
			20—48	1	050	185	
			48 & Finer	1	.030	200	
			[illegible]	2	1.80	41	S4, S2
			[illegible]	1	1.50	44	
			[illegible]	1	1.50	50	
			[illegible]	1	1.25	56	
			[illegible]	1	.75	60	
	225 to 275	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	1—2	2	.060	110	M2, M7
			3—10	1	.050	125	
			11—19	1	.050	150	
			20—48	1	.050	165	
			48 & Finer	1	.030	175	
			[illegible]	2	1.50	32	S4, S2
			[illegible]	1	1.25	38	
			[illegible]	1	1.25	45	
			[illegible]	1	1.25	50	
			[illegible]	1	.75	53	
	275 to 325	Hot Rolled, Normalized, Annealed or Quenched and Tempered	1—2	2	.045	95	M2, M7
			3—10	1	.045	110	
			11—19	1	.045	120	
			20—48	1	.045	130	
			48 & Finer	1	.030	140	
			[illegible]	2	1.15	29	S4, S2
			[illegible]	1	1.15	34	
			[illegible]	1	1.15	37	
			[illegible]	1	1.15	40	
			[illegible]	1	.75	43	
	325 to 375	Quenched and Tempered	1—2	2	.045	70	M3, M42
			3—10	1	.045	80	
			11—19	1	.025	100	
			20—48	1	.025	105	
			48 & Finer	1	.025	120	
			[illegible]	2	1.00	21	S4, S2
			[illegible]	1	1.00	24	
			[illegible]	1	.75	26	
			[illegible]	1	.75	28	
			[illegible]	1	.75	30	
High Carbon 1060 1075 1090 1064 1078 1095 1065 1080 1561 1069 1084 1566 1070 1085 1572 1074 1086	175 to 225	Hot Rolled, Normalized, Annealed or Cold Drawn	1—2	2	.070	125	M2, M7
			3—10	1	.070	135	
			11—19	1	.060	155	
			20—48	1	.050	175	
			48 & Finer	1	.030	190	
			[illegible]	2	1.50	40	S4, S2
			[illegible]	1	1.50	44	
			[illegible]	1	1.50	47	
			[illegible]	1	1.25	50	
			[illegible]	1	.75	53	

For hobbing Class 9 (per AGMA 390.03) or better gears, it may be necessary to reduce speeds and feeds by 50% and/or take 2 cuts. To meet finish requirements it may be necessary to try both conventional and climb cutting.

See section 16 for Cutting Fluid Recommendations.

*Feeds are based on the largest standard recommended hob diameter. When using a smaller hob diameter, the Feed must be reduced proportionally.

7.1 Gear Hobbing

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	NUMBER OF CUTS	FEED* PER REVOLUTION OF WORKPIECE in / mm	HOB SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
2. CARBON STEELS, WROUGHT (cont.) High Carbon (cont.) (materials listed on preceding page)	225 to 275	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	1—2	2	.060	100	M2, M7
			3—10	1	050	115	
			11—19	1	050	140	
			20—48	1	050	155	
			48 & Finer	1	030	165	
			25—13	2	1.50	30	S4, S2
			12—2.5	1	1.25	35	
			2—1.5	1	1.25	43	
			1—.5	1	1.25	47	
			.5 & Finer	1	.75	50	
	275 to 325	Hot Rolled, Normalized, Annealed or Quenched and Tempered	1—2	2	.045	85	M2, M7
			3—10	1	.045	100	
			11—19	1	.045	110	
			20—48	1	.045	120	
			48 & Finer	1	.030	130	
			25—13	2	1.15	26	S4, S2
			12—2.5	1	1.15	30	
			2—1.5	1	1.15	34	
			1—.5	1	1.15	37	
			.5 & Finer	1	.75	40	
	325 to 375	Quenched and Tempered	1—2	2	.045	65	M3, M42
			3—10	1	045	75	
			11—19	1	.025	95	
			20—48	1	.025	100	
			48 & Finer	1	.025	115	
			25—13	2	1.15	20	S5, S11
			12—2.5	1	1.15	23	
			2—1.5	1	95	29	
			1—.5	1	85	30	
			.5 & Finer	1	85	35	
3. CARBON AND [illegible] ALLOY STEELS (HIGH TEMPERATURE SERVICE) ASTM A369. Grades FPA, FPB, FP1, FP2, FP12	150 to 200	As Forged	1—2	2	.070	165	M2, M7
			3—10	1	.070	175	
			11—19	1	.060	185	
			20—48	1	.050	200	
			48 & Finer	1	.030	210	
			25—13	2	1.80	50	S4, S2
			12—2.5	1	1.80	53	
			2—1.5	1	1.50	58	
			1—.5	1	1.25	60	
			.5 & Finer	1	.75	64	
ASTM A369. Grades FP3b, FP11	150 to 200	Annealed or Normalized and Tempered	1—2	2	.070	135	M2, M7
			3—10	1	.070	145	
			11—19	1	.060	165	
			20—48	1	.050	185	
			48 & Finer	1	030	200	
			25—13	2	1.80	41	S4, S2
			12—2.5	1	1.80	44	
			2—1.5	1	1.50	48	
			1—.5	1	1.25	50	
			.5 & Finer	1	.75	54	
ASTM A369. Grades FP5, FP7, FP9, FP21, FP22	150 to 200	Annealed or Normalized and Tempered	1—2	2	.060	110	M2, M7
			3—10	1	.050	125	
			11—19	1	.050	150	
			20—48	1	.050	165	
			48 & Finer	1	.030	175	
			25—13	2	1.65	34	S4, S2
			12—2.5	1	1.65	38	
			2—1.5	1	1.35	43	
			1—.5	1	1.35	50	
			.5 & Finer	1	.75	54	

For hobbing Class 9 (per AGMA 390.03) or better gears, it may be necessary to reduce speeds and feeds by 50% and/or take 2 cuts. To meet finish requirements it may be necessary to try both conventional and climb cutting.

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*Feeds are based on the largest standard recommended hob diameter. When using a smaller hob diameter, the Feed must be reduced proportionally.

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	NUMBER OF CUTS	FEED* PER REVOLUTION OF WORKPIECE in / mm	HOB SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
4. FREE MACHINING ALLOY STEELS, WROUGHT **Medium Carbon Resulfurized** 4140 4140Se 4142Te 4145Se 4147Te 4150	150 to 200	Hot Rolled, Normalized, Annealed or Cold Drawn	1—2	2	.060	145	M2, M7
			3—10	1	.060	155	
			11—19	1	.060	165	
			20—48	1	.050	180	
			48 & Finer	1	030	200	
			25—13	2	1.50	44	64, 62
			12—2.5	1	1.50	47	
			2—1.5	1	1.50	50	
			1—.5	1	1.25	55	
			.5 & Finer	1	.75	60	
	200 to 250	Hot Rolled, Normalized, Annealed or Cold Drawn	1—2	2	.060	120	M2, M7
			3—10	1	.060	130	
			11—19	1	.060	140	
			20—48	1	.050	160	
			48 & Finer	1	.030	180	
			25—13	2	1.50	37	34, 32
			12—2.5	1	1.50	40	
			2—1.5	1	1.50	43	
			1—.5	1	1.25	46	
			.5 & Finer	1	.75	50	
	275 to 325	Quenched and Tempered	1—2	2	.045	90	M2, M7
			3—10	1	.045	100	
			11—19	1	.045	110	
			20—48	1	.045	120	
			48 & Finer	1	.030	130	
			25—13	2	1.15	27	64, 62
			12—2.5	1	1.15	30	
			2—1.5	1	1.15	34	
			1—.5	1	1.15	37	
			.5 & Finer	1	.75	40	
	325 to 375	Quenched and Tempered	1—2	2	.045	65	M3, M42
			3—10	1	.045	75	
			11—19	1	025	95	
			20—48	1	.025	100	
			48 & Finer	1	.025	135	
			25—13	2	1.15	25	60, 611
			12—2.5	1	1.15	28	
			2—1.5	1	1.15	30	
			1—.5	1	1.15	33	
			.5 & Finer	1	.75	37	
Medium and High Carbon Leaded 41L30 43L40 41L40 51L32 41L45 52L100 41L47 86L20 41L50 86L40	150 to 200	Hot Rolled, Normalized, Annealed or Cold Drawn	1—2	2	.060	170	M2, M7
			3—10	1	.060	180	
			11—19	1	.060	190	
			20—48	1	.050	200	
			48 & Finer	1	.030	220	
			25—13	2	1.50	52	64, 62
			12—2.5	1	1.50	55	
			2—1.5	1	1.50	58	
			1—.5	1	1.25	62	
			.5 & Finer	1	.75	65	
	200 to 250	Hot Rolled, Normalized, Annealed or Cold Drawn	1—2	2	.060	140	M2, M7
			3—10	1	.060	155	
			11—19	1	.060	170	
			20—48	1	.050	185	
			48 & Finer	1	.030	200	
			25—13	2	1.50	44	64, 62
			12—2.5	1	1.50	47	
			2—1.5	1	1.50	50	
			1—.5	1	1.25	55	
			.5 & Finer	1	.75	60	

For hobbing Class 9 (per AGMA 390.03) or better gears, it may be necessary to reduce speeds and feeds by 50% and/or take 2 cuts. To meet finish requirements it may be necessary to try both conventional and climb cutting.

See section 16 for Cutting Fluid Recommendations.

*Feeds are based on the largest standard recommended hob diameter. When using a smaller hob diameter, the Feed must be reduced proportionally.

7.1 Gear Hobbing

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	NUMBER OF CUTS	FEED* PER REVOLUTION OF WORKPIECE in / mm	HOB SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
4. FREE MACHINING ALLOY STEELS, WROUGHT (cont.) Medium and High Carbon Leaded (cont.) (materials listed on preceding page)	275 to 325	Quenched and Tempered	1—2	2	.045	120	M2, M7
			3—10	1	.045	140	
			11—19	1	.045	145	
			20—48	1	.045	150	
			48 & Finer	1	.030	165	
			25—13	2	1.15	37	S4, S2
			12—2.5	1	1.15	43	
			2—1.5	1	1.15	44	
			1—.5	1	1.15	46	
			.5 & Finer	1	.75	50	
	325 to 375	Quenched and Tempered	1—2	2	.045	70	M3, M42
			3—10	1	.045	90	
			11—19	1	.045	110	
			20—48	1	.045	120	
			48 & Finer	1	.030	130	
			25—13	2	1.15	21	S5, S11
			12—2.5	1	1.15	27	
			2—1.5	1	1.15	34	
			1—.5	1	1.15	37	
			.5 & Finer	1	.75	40	
5. ALLOY STEELS, WROUGHT Low Carbon 4012 4615 4817 8617 4023 4617 4820 8620 4024 4620 5015 8622 4118 4621 5115 8822 4320 4718 5120 9310 4419 4720 6118 94B15 4422 4815 8115 94B17	125 to 175	Hot Rolled, Annealed or Cold Drawn	1—2	2	.060	160	M2, M7
			3—10	1	060	170	
			11—19	1	060	180	
			20—48	1	.050	190	
			48 & Finer	1	.030	210	
			25—13	2	1.50	49	S4, S2
			12—2.5	1	1.50	52	
			2—1.5	1	1.50	55	
			1—.5	1	1.25	58	
			.5 & Finer	1	.75	64	
	175 to 225	Hot Rolled, Annealed or Cold Drawn	1—2	2	.060	130	M2, M7
			3—10	1	.060	140	
			11—19	1	060	150	
			20—48	1	.050	170	
			48 & Finer	1	.030	190	
			25—13	2	1.50	40	S4, S2
			12—2.5	1	1.50	43	
			2—1.5	1	1.50	46	
			1—.5	1	1.25	52	
			.5 & Finer	1	.75	58	
	225 to 275	Hot Rolled, Normalized, Annealed or Cold Drawn	1—2	2	.060	105	M2, M7
			3—10	1	.050	115	
			11—19	1	.050	130	
			20—48	1	.050	150	
			48 & Finer	1	.030	165	
			25—13	2	1.50	32	S4, S2
			12—2.5	1	1.25	35	
			2—1.5	1	1.25	40	
			1—.5	1	1.25	46	
			.5 & Finer	1	.75	50	
	275 to 325	Normalized or Quenched and Tempered	1—2	2	.045	90	M2, M7
			3—10	1	.045	100	
			11—19	1	.045	110	
			20—48	1	.045	120	
			48 & Finer	1	.030	130	
			25—13	2	1.15	27	S4, S2
			12—2.5	1	1.15	30	
			2—1.5	1	1.15	34	
			1—.5	1	1.15	37	
			.5 & Finer	1	.75	40	

For hobbing Class 9 (per AGMA 390.03) or better gears, it may be necessary to reduce speeds and feeds by 50% and/or take 2 cuts. To meet finish requirements it may be necessary to try both conventional and climb cutting

See section 16 for Cutting Fluid Recommendations.

*Feeds are based on the largest standard recommended hob diameter. When using a smaller hob diameter, the Feed must be reduced proportionally.

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	NUMBER OF CUTS	FEED* PER REVOLUTION OF WORKPIECE in / mm	HOB SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
5. ALLOY STEELS, WROUGHT (cont.) **Low Carbon (cont.)** (materials listed on preceding page)	325 to 375	Normalized or Quenched and Tempered	1—2	2	.045	65	M3, M42
			3—10	1	.045	70	
			11—19	1	.025	75	
			20—48	1	.025	90	
			48 & Finer	1	.025	100	
			25—13	2	1.15	20	S5, S11
			12—2.5	1	1.15	21	
			2—1.5	1	.65	23	
			1—.5	1	.65	27	
			.5 & Finer	1	.65	30	
Medium Carbon 1330 4427 81B45 1335 4626 8625 1340 50B40 8627 1345 50B44 8630 4027 5046 8637 4028 50B46 8640 4032 50B50 8642 4037 5060 8645 4042 50B60 86B45 4047 5130 8650 4130 5132 8655 4135 5135 8660 4137 5140 8740 4140 5145 8742 4142 5147 9254 4145 5150 9255 4147 5155 9260 4150 5160 94B30 4161 51B60 4340 6150	175 to 225	Hot Rolled, Annealed or Cold Drawn	1—2	2	060	125	M2, M7
			3—10	1	.060	135	
			11—19	1	050	145	
			20—48	1	.050	160	
			48 & Finer	1	.030	180	
			25—13	2	1.50	36	S4, S2
			12—2.5	1	1.50	41	
			2—1.5	1	1.25	44	
			1—.5	1	1.25	49	
			.5 & Finer	1	.75	55	
	225 to 275	Annealed, Normalized, Cold Drawn or Quenched and Tempered	1—2	2	.060	100	M2, M7
			3—10	1	.050	110	
			11—19	1	.050	125	
			20—48	1	.050	140	
			48 & Finer	1	.030	155	
			25—13	2	1.50	30	S4, S2
			12—2.5	1	1.25	34	
			2—1.5	1	1.25	38	
			1—.5	1	1.25	43	
			.5 & Finer	1	.75	47	
	275 to 325	Normalized or Quenched and Tempered	1—2	2	.045	85	M2, M7
			3—10	1	.045	95	
			11—19	1	045	105	
			20—48	1	.045	110	
			48 & Finer	1	.030	120	
			25—13	2	1.15	26	S4, S2
			12—2.5	1	1.15	29	
			2—1.5	1	1.15	32	
			1—.5	1	1.15	34	
			.5 & Finer	1	.75	37	
	325 to 375	Normalized or Quenched and Tempered	1—2	2	.045	60	M3, M42
			3—10	1	.045	65	
			11—19	1	025	75	
			20—48	1	.025	80	
			48 & Finer	1	.025	95	
			25—13	2	1.15	16	S5, S11
			12—2.5	1	1.15	20	
			2—1.5	1	.65	23	
			1—.5	1	.65	24	
			.5 & Finer	1	.65	29	
High Carbon 50100 51100 52100 M-50	175 to 225	Hot Rolled, Annealed or Cold Drawn	1—2	2	.060	115	M2, M7
			3—10	1	.060	125	
			11—19	1	.050	135	
			20—48	1	.050	150	
			48 & Finer	1	.030	170	
			25—13	2	1.50	35	S4, S2
			12—2.5	1	1.50	38	
			2—1.5	1	1.25	41	
			1—.5	1	1.25	46	
			.5 & Finer	1	.75	52	

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7.1 Gear Hobbing

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	NUMBER OF CUTS	FEED* PER REVOLUTION OF WORKPIECE in / mm	HOB SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
5. ALLOY STEELS, WROUGHT (cont.) **High Carbon (cont.)** (materials listed on preceding page)	225 to 275	Normalized, Cold Drawn or Quenched and Tempered	1—2	2	.060	90	M2, M7
			3—10	1	.050	100	
			11—19	1	.050	115	
			20—48	1	.050	130	
			48 & Finer	1	.030	145	
			25—13	2	1.50	27	S4, S2
			12—2.5	1	1.25	30	
			2—1.5	1	1.25	35	
			1—.5	1	1.25	40	
			.5 & Finer	1	.75	44	
	275 to 325	Normalized or Quenched and Tempered	1—2	2	.045	80	M2, M7
			3—10	1	045	90	
			11—19	1	045	100	
			20—48	1	.045	105	
			48 & Finer	1	.030	115	
			25—13	2	1.15	24	S4, S2
			12—2.5	1	1.15	27	
			2—1.5	1	1.15	30	
			1—.5	1	1.15	32	
			.5 & Finer	1	.75	35	
	325 to 375	Normalized or Quenched and Tempered	1—2	2	.045	55	M3, M42
			3—10	1	045	60	
			11—19	1	.025	70	
			20—48	1	025	75	
			48 & Finer	1	025	90	
			25—13	2	1.15	17	S5, S11
			12—2.5	1	1.15	18	
			2—1.5	1	.65	21	
			1—.5	1	.65	23	
			.5 & Finer	1	.65	27	
6. HIGH STRENGTH STEELS, WROUGHT 300M 98BV40 4330V D6ac 4340 H11 4340Si H13	225 to 300	Annealed	1—2	2	.060	80	M2, M7
			3—10	1	.050	95	
			11—19	1	.050	105	
			20—48	1	.050	110	
			48 & Finer	1	.030	120	
			25—13	2	1.50	24	S4, S2
			12—2.5	1	1.25	29	
			2—1.5	1	1.25	32	
			1—.5	1	1.25	34	
			.5 & Finer	1	.75	37	
	300 to 350	Normalized	1—2	2	.045	65	M2, M7
			3—10	1	.045	80	
			11—19	1	.045	90	
			20—48	1	.045	95	
			48 & Finer	1	.030	105	
			25—13	2	1.15	20	S4, S2
			12—2.5	1	1.15	24	
			2—1.5	1	1.15	27	
			1—.5	1	1.15	29	
			.5 & Finer	1	.75	32	
HP 9-4-20 HP 9-4-25 HP 9-4-30 HP 9-4-45	325 to 375	Annealed	1—2	2	.045	60	M3, M42
			3—10	1	.045	70	
			11—19	1	.025	80	
			20—48	1	.025	85	
			48 & Finer	1	.025	95	
			25—13	2	1.15	18	S5, S11
			12—2.5	1	1.15	21	
			2—1.5	1	.65	24	
			1—.5	1	.65	26	
			.5 & Finer	1	.65	29	

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MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	NUMBER OF CUTS	FEED* PER REVOLUTION OF WORKPIECE in / mm	HOB SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
7. MARAGING STEELS, WROUGHT 120 Grade 180 Grade	275 to 325	Annealed	1—2	2	.045	120	M2, M7
			3—10	1	045	130	
			11—19	1	.045	145	
			20—48	1	.045	155	
			48 & Finer	1	030	170	
			25—13	2	1.15	37	S4, S2
			12—2.5	1	1.15	40	
			2—1.5	1	1.15	44	
			1—.5	1	1.15	47	
			.5 & Finer	1	.75	52	
ASTM A538. Grades A, B, C 200 Grade 250 Grade 300 Grade 350 Grade HY230	275 to 325	Annealed	1—2	2	.045	100	M2, M7
			3—10	1	045	110	
			11—19	1	.045	120	
			20—48	1	.045	130	
			48 & Finer	1	030	140	
			25—13	2	1.15	30	S4, S2
			12—2.5	1	1.15	34	
			2—1.5	1	1.15	37	
			1—.5	1	1.15	40	
			.5 & Finer	1	.75	43	
8. TOOL STEELS, WROUGHT **High Speed** M1 M2 M6 M10 T1 T2 T6	200 to 250	Annealed	1—2	2	.045	40	M2, M7
			3—10	1	.045	45	
			11—19	1	.045	55	
			20—48	1	.045	60	
			48 & Finer	1	.030	80	
			25—13	2	1.15	12	S4, S2
			12—2.5	1	1.15	14	
			2—1.5	1	1.15	17	
			1—.5	1	1.15	18	
			.5 & Finer	1	.75	24	
High Speed M3-1 M34 M46 M3-2 M36 M47 M4 M41 T4 M7 M42 T5 M30 M43 T8 M33 M44 T15	225 to 275	Annealed	1—2	2	.045	35	M2, M7
			3—10	1	.045	40	
			11—19	1	.025	50	
			20—48	1	.025	55	
			48 & Finer	1	.025	75	
			25—13	2	1.15	11	S4, S2
			12—2.5	1	1.15	12	
			2—1.5	1	.65	15	
			1—.5	1	.65	17	
			.5 & Finer	1	.65	23	
Hot Work H10 H22 H11 H23 H12 H24 H13 H25 H14 H26 H19 H42 H21	150 to 200	Annealed	1—2	2	.060	70	M2, M7
			3—10	1	.060	75	
			11—19	1	.060	85	
			20—48	1	050	90	
			48 & Finer	1	.030	110	
			25—13	2	1.50	21	S4, S2
			12—2.5	1	1.50	23	
			2—1.5	1	1.50	26	
			1—.5	1	1.25	27	
			.5 & Finer	1	.75	34	
	200 to 250	Annealed	1—2	2	.060	55	M2, M7
			3—10	1	.060	60	
			11—19	1	.060	70	
			20—48	1	.050	75	
			48 & Finer	1	.030	95	
			25—13	2	1.50	27	S4, S2
			12—2.5	1	1.50	16	
			2—1.5	1	1.50	21	
			1—.5	1	1.25	23	
			.5 & Finer	1	.75	29	

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7.1 Gear Hobbing

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	NUMBER OF CUTS	FEED* PER REVOLUTION OF WORKPIECE in / mm	HOB SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
8. TOOL STEELS, WROUGHT (cont.) **Hot Work (cont.)** (materials listed on preceding page)	325 to 375	Quenched and Tempered	1—2	2	.045	45	M3, M42
			3—10	1	.045	50	
			11—19	1	.025	60	
			20—48	1	.025	65	
			48 & Finer	1	.025	85	
			25—13	2	1.15	14	S5, S11
			12—2.5	1	1.15	15	
			2—1.5	1	.65	18	
			1—.5	1	.65	20	
			.5 & Finer	1	.65	26	
Cold Work A2 D3 A3 D4 A4 D5 A6 D7 A7 O1 A8 O2 A9 O6 A10 O7 D2	200 to 250	Annealed	1—2	2	.060	55	M2, M7
			3—10	1	.060	60	
			11—19	1	.060	70	
			20—48	1	.050	75	
			48 & Finer	1	.030	95	
			25—13	2	1.50	17	S4, S2
			12—2.5	1	1.50	18	
			2—1.5	1	1.50	21	
			1—.5	1	1.25	23	
			.5 & Finer	1	.75	29	
Shock Resisting S1 S2 S5 S6 S7	175 to 225	Annealed	1—2	2	.060	70	M2, M7
			3—10	1	.060	75	
			11—19	1	.060	85	
			20—48	1	.050	90	
			48 & Finer	1	.030	110	
			25—13	2	1.50	21	S4, S2
			12—2.5	1	1.50	23	
			2—1.5	1	1.50	26	
			1—.5	1	1.25	27	
			.5 & Finer	1	.75	34	
Mold P2 P4 P5 P6	100 to 150	Annealed	1—2	2	.060	95	M2, M7
			3—10	1	.060	100	
			11—19	1	.060	110	
			20—48	1	.050	115	
			48 & Finer	1	.030	125	
			25—13	2	1.50	29	S4, S2
			12—2.5	1	1.50	30	
			2—1.5	1	1.50	36	
			1—.5	1	1.25	38	
			.5 & Finer	1	.75	46	
Mold P20 P21	150 to 200	Annealed	1—2	2	.060	70	M2, M7
			3—10	1	.060	75	
			11—19	1	.060	85	
			20—48	1	.050	90	
			48 & Finer	1	.030	110	
			25—13	2	1.50	21	S4, S2
			12—2.5	1	1.50	23	
			2—1.5	1	1.50	26	
			1—.5	1	1.25	27	
			.5 & Finer	1	.75	34	

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MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	NUMBER OF CUTS	FEED* PER REVOLUTION OF WORKPIECE in / mm	HOB SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
Special Purpose L2 L6 L7	150 to 200	Annealed	1—2	2	060	65	M2, M7
			3—10	1	060	70	
			11—19	1	060	80	
			20—48	1	050	85	
			48 & Finer	1	030	105	
			25—13	2	1.50	20	S4, S2
			12—2.5	1	1.50	21	
			2—1.5	1	1.50	24	
			1—.5	1	1.25	26	
			.5 & Finer	1	.75	32	
Special Purpose F1 F2	200 to 250	Annealed	1—2	2	060	50	M2, M7
			3—10	1	060	55	
			11—19	1	060	65	
			20—48	1	050	70	
			48 & Finer	1	030	90	
			25—13	2	1.50	15	S4, S2
			12—2.5	1	1.50	17	
			2—1.5	1	1.50	20	
			1—.5	1	1.25	21	
			.5 & Finer	1	.75	27	
Water Hardening W1, W2, W5 SAE J438b, Types W108, W109, W110, W112, W209, W210, W310	150 to 200	Annealed	1—2	2	.060	105	M2, M7
			3—10	1	.060	110	
			11—19	1	.060	120	
			20—48	1	.050	125	
			48 & Finer	1	.030	145	
			25—13	2	1.50	32	S4, S2
			12—2.5	1	1.50	34	
			2—1.5	1	1.50	37	
			1—.5	1	1.25	38	
			.5 & Finer	1	.75	44	
9. NITRIDING STEELS, WROUGHT Nitralloy 125 Nitralloy 135 Nitralloy 135 Mod. Nitralloy 225 Nitralloy 230 Nitralloy EZ Nitralloy N Nitrex 1	200 to 250	Annealed	1—2	2	.045	85	M2, M7
			3—10	1	.045	100	
			11—19	1	.045	110	
			20—48	1	.045	115	
			48 & Finer	1	.030	125	
			25—13	2	1.15	26	S4, S2
			12—2.5	1	1.15	30	
			2—1.5	1	1.15	34	
			1—.5	1	1.15	35	
			.5 & Finer	1	.75	38	
	300 to 350	Normalized or Quenched and Tempered	1—2	2	.045	65	M2, M7
			3—10	1	.045	80	
			11—19	1	.025	90	
			20—48	1	.025	95	
			48 & Finer	1	.025	105	
			25—13	2	1.15	20	S4, S2
			12—2.5	1	1.15	24	
			2—1.5	1	.65	27	
			1—.5	1	.65	29	
			.5 & Finer	1	.65	32	
12. FREE MACHINING STAINLESS STEELS, WROUGHT Ferritic 430F 430F Se	135 to 185	Annealed	1—2	2	.060	175	M2, M7
			3—10	1	.060	205	
			11—19	1	.060	220	
			20—48	1	.050	235	
			48 & Finer	1	.030	250	
			25—13	2	1.50	53	S4, S2
			12—2.5	1	1.50	62	
			2—1.5	1	1.50	67	
			1—.5	1	1.25	72	
			.5 & Finer	1	.75	76	

For hobbing Class 9 (per AGMA 390.03) or better gears, it may be necessary to reduce speeds and feeds by 50% and/or take 2 cuts. To meet finish requirements it may be necessary to try both conventional and climb cutting

See section 16 for Cutting Fluid Recommendations

*Feeds are based on the largest standard recommended hob diameter. When using a smaller hob diameter, the Feed must be reduced proportionally.

7.1 Gear Hobbing

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	NUMBER OF CUTS	FEED* PER REVOLUTION OF WORKPIECE in / mm	HOB SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
12. FREE MACHINING STAINLESS STEELS, WROUGHT (cont.) **Austenitic** 203EZ 303Pb; 303 303 Plus X; 303MA 303Se	135 to 185	Annealed	1—2	2	.060	125	M2, M7
			3—10	1	060	155	
			11—19	1	060	170	
			20—48	1	.050	185	
			48 & Finer	1	.030	200	
			25—13	2	1.50	38	S4, S2
			12—2.5	1	1.50	47	
			2—1.5	1	1.50	52	
			1—.5	1	1.25	56	
			.5 & Finer	1	.75	60	
	225 to 275	Cold Drawn	1—2	2	060	115	M2, M7
			3—10	1	.050	135	
			11—19	1	050	155	
			20—48	1	050	175	
			48 & Finer	1	.030	195	
			25—13	2	1.50	35	S4, S2
			12—2.5	1	1.25	41	
			2—1.5	1	1.25	47	
			1—.5	1	1.25	53	
			.5 & Finer	1	.75	59	
Martensitic 416; 416 Plus X; 416Se; 420F; 420F Se; 440F; 440F Se	135 to 185	Annealed	1—2	2	.060	175	M2, M7
			3—10	1	.060	205	
			11—19	1	.060	220	
			20—48	1	.050	235	
			48 & Finer	1	.030	250	
			25—13	2	1.50	53	S4, S2
			12—2.5	1	1.50	62	
			2—1.5	1	1.50*	67	
			1—.5	1	1.25*	72	
			.5 & Finer	1	.75	76	
	185 to 240	Annealed or Cold Drawn	1—2	2	.060	165	M2, M7
			3—10	1	060	195	
			11—19	1	060	210	
			20—48	1	050	225	
			48 & Finer	1	.030	240	
			25—13	2	1.50	50	S4, S2
			12—2.5	1	1.50	59	
			2—1.5	1	1.50	64	
			1—.5	1	1.25	69	
			.5 & Finer	1	.75	73	
	275 to 325	Quenched and Tempered	1—2	2	.045	100	M2, M7
			3—10	1	045	135	
			11—19	1	.045	155	
			20—48	1	.045	160	
			48 & Finer	1	.030	175	
			25—13	2	1.15	30	S4, S2
			12—2.5	1	1.15	41	
			2—1.5	1	1.15	47	
			1—.5	1	1.15	46	
			.5 & Finer	1	.75	58	
13. STAINLESS STEELS, WROUGHT **Ferritic** 405 434; 409 436; 429 442; 430 446	135 to 185	Annealed	1—2	2	060	125	M2, M7
			3—10	1	.060	135	
			11—19	1	060	150	
			20—48	1	.050	160	
			48 & Finer	1	.030	170	
			25—13	2	1.50	38	S4, S2
			12—2.5	1	1.50	44	
			2—1.5	1	1.50	48	
			1—.5	1	1.25	49	
			.5 & Finer	1	.75	52	

For hobbing Class 9 (per AGMA 390 03) or better gears, it may be necessary to reduce speeds and feeds by 50% and/or take 2 cuts. To meet finish requirements it may be necessary to try both conventional and climb cutting.

See section 16 for Cutting Fluid Recommendations.

*Feeds are based on the largest standard recommended hob diameter. When using a smaller hob diameter, the Feed must be reduced proportionally.

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	NUMBER OF CUTS	FEED* PER REVOLUTION OF WORKPIECE in / mm	HOB SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
Austenitic 201 308 202 321 301 347 302 348 304 384 304L 385 305	135 to 185	Annealed	1—2	2	.060	95	M2, M7
			3—10	1	.060	105	
			11—19	1	060	120	
			20—48	1	050	130	
			48 & Finer	1	.030	140	
			25—13	2	1.50	29	S4, S2
			12—2.5	1	1.50	32	
			2—1.5	1	1.50	37	
			1—.5	1	1.25	40	
			.5 & Finer	1	.75	43	
	225 to 275	Cold Drawn	1—2	2	060	90	M2, M7
			3—10	1	.050	100	
			11—19	1	.050	115	
			20—48	1	050	125	
			48 & Finer	1	.030	135	
			25—13	2	1.50	27	S4, S2
			12—2.5	1	1.25	30	
			2—1.5	1	1.25	35	
			1—.5	1	1.25	38	
			.5 & Finer	1	.75	41	
Austenitic 302B 314 309 316 309S 316L 310 317 310S 330	135 to 185	Annealed	1—2	2	.060	85	M2, M7
			3—10	1	.060	95	
			11—19	1	.060	110	
			20—48	1	.050	120	
			48 & Finer	1	030	130	
			25—13	2	1.50	26	S4, S2
			12—2.5	1	1.50	28	
			2—1.5	1	1.50	34	
			1—.5	1	1.25	37	
			.5 & Finer	1	.75	40	
	225 to 275	Cold Drawn	1—2	2	.060	70	M2, M7
			3—10	1	.050	80	
			11—19	1	.050	90	
			20—48	1	.050	105	
			48 & Finer	1	.030	120	
			25—13	2	1.50	21	S4, S2
			12—2.5	1	1.25	24	
			2—1.5	1	1.25	27	
			1—.5	1	1.25	32	
			.5 & Finer	1	.75	37	
Austenitic Nitronic 32 Nitronic 33 Nitronic 40 Nitronic 50 Nitronic 60	210 to 250	Annealed	1—2	2	060	60	M2, M7
			3—10	1	.050	70	
			11—19	1	050	80	
			20—48	1	.050	90	
			48 & Finer	1	.030	100	
			25—13	2	1.50	18	S4, S2
			12—2.5	1	1.25	21	
			2—1.5	1	1.25	24	
			1—.5	1	1.25	27	
			.5 & Finer	1	.75	30	
Martensitic 403 410 420 422 501 502	135 to 175	Annealed	1—2	2	.060	110	M2, M7
			3—10	1	.060	130	
			11—19	1	060	145	
			20—48	1	.050	155	
			48 & Finer	1	.030	170	
			25—13	2	1.50	34	S4, S2
			12—2.5	1	1.50	40	
			2—1.5	1	1.50	44	
			1—.5	1	1.25	47	
			.5 & Finer	1	.75	52	

For hobbing Class 9 (per AGMA 390.03) or better gears, it may be necessary to reduce speeds and feeds by 50% and/or take 2 cuts To meet finish requirements it may be necessary to try both conventional and climb cutting.

See section 16 for Cutting Fluid Recommendations.

*Feeds are based on the largest standard recommended hob diameter When using a smaller hob diameter, the Feed must be reduced proportionally.

7.1 Gear Hobbing

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	NUMBER OF CUTS	FEED* PER REVOLUTION OF WORKPIECE in / mm	HOB SPEED fpm / m/min.	HSS TOOL MATERIAL AISI / ISO
13. STAINLESS STEELS, WROUGHT (cont.) Martensitic (cont.) (materials listed on preceding page)	175 to 225	Annealed	1—2	2	060	100	M2, M7
			3—10	1	060	120	
			11—19	1	060	135	
			20—48	1	050	145	
			48 & Finer	1	030	160	
			25—13	2	1.50	30	S4, S2
			12—2.5	1	1.50	37	
			2—1.5	1	1.50	41	
			1—.5	1	1.25	44	
			.5 & Finer	1	.75	49	
	275 to 325	Quenched and Tempered	1—2	2	.045	60	M2, M7
			3—10	1	045	80	
			11—19	1	045	95	
			20—48	1	045	105	
			48 & Finer	1	030	120	
			25—13	2	1.15	18	S4, S2
			12—2.5	1	1.15	24	
			2—1.5	1	1.15	29	
			1—.5	1	1.15	32	
			.5 & Finer	1	.75	37	
Martensitic 414 431 Greek Ascoloy	225 to 275	Annealed	1—2	2	060	70	M2, M7
			3—10	1	050	90	
			11—19	1	050	105	
			20—48	1	050	115	
			48 & Finer	1	.030	130	
			25—13	2	1.50	21	S4, S2
			12—2.5	1	1.25	27	
			2—1.5	1	1.25	32	
			1—.5	1	1.25	35	
			.5 & Finer	1	.75	40	
	275 to 325	Quenched and Tempered	1—2	2	.045	55	M2, M7
			3—10	1	.045	75	
			11—19	1	.045	90	
			20—48	1	045	100	
			48 & Finer	1	030	115	
			25—13	2	1.15	17	S4, S2
			12—2.5	1	1.15	23	
			2—1.5	1	1.15	27	
			1—.5	1	1.15	30	
			.5 & Finer	1	.75	35	
Martensitic 440A 440B 440C	225 to 275	Annealed	1—2	2	060	60	M2, M7
			3—10	1	.050	80	
			11—19	1	.050	95	
			20—48	1	.050	105	
			48 & Finer	1	.030	120	
			25—13	2	1.50	18	S4, S2
			12—2.5	1	1.25	24	
			2—1.5	1	1.25	29	
			1—.5	1	1.25	32	
			.5 & Finer	1	.75	37	
	275 to 325	Quenched and Tempered	1—2	2	.045	50	M2, M7
			3—10	1	.045	70	
			11—19	1	045	85	
			20—48	1	.045	95	
			48 & Finer	1	.030	110	
			25—13	2	1.15	15	S4, S2
			12—2.5	1	1.15	21	
			2—1.5	1	1.15	26	
			1—.5	1	1.15	29	
			.5 & Finer	1	.75	34	

For hobbing Class 9 (per AGMA 390.03) or better gears, it may be necessary to reduce speeds and feeds by 50% and/or take 2 cuts. To meet finish requirements it may be necessary to try both conventional and climb cutting.

See section 16 for Cutting Fluid Recommendations.

*Feeds are based on the largest standard recommended hob diameter. When using a smaller hob diameter, the Feed must be reduced proportionally.

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	NUMBER OF CUTS	FEED* PER REVOLUTION OF WORKPIECE in / mm	HOB SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
14. PRECIPITATION HARDENING STAINLESS STEELS, WROUGHT 15-5 PH 16-6 PH 17-4 PH 17-7 PH 17-14 Cu Mo AF-71 AFC-77 Almar 362 (AM-362) AM-350 AM-355 AM-363 Custom 450 Custom 455 HNM PH 13-8 Mo PH 14-8 Mo PH 15-7 Mo Stainless W	150 to 200	Solution Treated	1—2	2	060	65	M2, M7
			3—10	1	060	85	
			11—19	1	.060	100	
			20—48	1	050	110	
			48 & Finer	1	030	125	
			25—13	2	1.50	20	S4, S2
			12—2.5	1	1.50	26	
			2—1.5	1	1.50	30	
			1—.5	1	1.25	34	
			.5 & Finer	1	.75	38	
	275 to 325	Solution Treated or Hardened	1—2	2	.045	60	M2, M7
			3—10	1	.045	80	
			11—19	1	.045	95	
			20—48	1	045	105	
			48 & Finer	1	.030	120	
			25—13	2	1.15	18	S4, S2
			12—2.5	1	1.15	24	
			2—1.5	1	1.15	29	
			1—.5	1	1.15	32	
			.5 & Finer	1	.75	37	
	325 to 375	Solution Treated or Hardened	1—2	2	.045	50	M3, M42
			3—10	1	.045	70	
			11—19	1	025	85	
			20—48	1	.025	95	
			48 & Finer	1	.025	110	
			25—13	2	1.15	15	S5, S11
			12—2.5	1	1.15	21	
			2—1.5	1	.65	26	
			1—.5	1	.65	29	
			.5 & Finer	1	.65	34	
15. CARBON STEELS, CAST **Low Carbon** ASTM A426: Grade CP1 1010 1020	100 to 150	Annealed, Normalized or Normalized and Tempered	1—2	2	.060	170	M2, M7
			3—10	1	.060	200	
			11—19	1	.060	215	
			20—48	1	.050	230	
			48 & Finer	1	030	245	
			25—13	2	1.50	52	S4, S2
			12—2.5	1	1.50	60	
			2—1.5	1	1.50	66	
			1—.5	1	1.25	70	
			.5 & Finer	1	.75	75	
Medium Carbon ASTM A352 Grades LCA, LCB, LCC ASTM A356. Grade 1 1030 1040 1050	125 to 175	Annealed, Normalized or Normalized and Tempered	1—2	2	.060	130	M2, M7
			3—10	1	.060	150	
			11—19	1	.060	165	
			20—48	1	.050	180	
			48 & Finer	1	.030	195	
			25—13	2	1.50	40	S4, S2
			12—2.5	1	1.50	46	
			2—1.5	1	1.50	50	
			1—.5	1	1.25	55	
			.5 & Finer	1	.75	59	
	175 to 225	Annealed, Normalized or Normalized and Tempered	1—2	2	.060	110	M2, M7
			3—10	1	060	125	
			11—19	1	.060	145	
			20—48	1	.050	150	
			48 & Finer	1	.030	165	
			25—13	2	1.50	34	S4, S2
			12—2.5	1	1.50	38	
			2—1.5	1	1.50	44	
			1—.5	1	1.25	46	
			.5 & Finer	1	.75	50	

For hobbing Class 9 (per AGMA 390.03) or better gears, it may be necessary to reduce speeds and feeds by 50% and/or take 2 cuts. To meet finish requirements it may be necessary to try both conventional and climb cutting

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7.1 Gear Hobbing

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	NUMBER OF CUTS	FEED* PER REVOLUTION OF WORKPIECE in / mm	HOB SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
15. CARBON STEELS, CAST (cont.) **Medium Carbon (cont.)** (materials listed on preceding page)	250 to 300	Quenched and Tempered	1—2	2	045	85	M2, M7
			3—10	1	.045	95	
			11—19	1	.045	115	
			20—48	1	.045	120	
			48 & Finer	1	.030	130	
			25—13	2	1.15	26	S4, S2
			12—2.5	1	1.15	29	
			2—1.5	1	1.15	35	
			1—.5	1	1.15	37	
			.5 & Finer	1	.75	40	
16. ALLOY STEELS, CAST **Low Carbon** ASTM A217 Grade WC9 ASTM A352. Grades LC3, LC4 ASTM A426 Grades CP2, CP5, CP5b, CP11, CP12, CP15, CP21, CP22 1320 2320 4120 8020 2315 4110 4320 8620	150 to 200	Annealed, Normalized or Normalized and Tempered	1—2	2	.060	130	M2, M7
			3—10	1	.060	150	
			11—19	1	060	165	
			20—48	1	.050	175	
			48 & Finer	1	.030	190	
			25—13	2	1.50	40	S4, S2
			12—2.5	1	1.50	46	
			2—1.5	1	1.50	50	
			1—.5	1	1.25	53	
			.5 & Finer	1	.75	58	
	200 to 225	Annealed, Normalized or Normalized and Tempered	1—2	2	.060	110	M2, M7
			3—10	1	.060	130	
			11—19	1	060	145	
			20—48	1	050	155	
			48 & Finer	1	.030	170	
			25—13	2	1.50	34	S4, S2
			12—2.5	1	1.50	40	
			2—1.5	1	1.50	44	
			1—.5	1	1.25	47	
			.5 & Finer	1	.75	52	
	250 to 300	Quenched and Tempered	1—2	2	.045	90	M2, M7
			3—10	1	045	100	
			11—19	1	.045	110	
			20—48	1	.045	120	
			48 & Finer	1	030	130	
			25—13	2	1.15	27	S4, S2
			12—2.5	1	1.15	30	
			2—1.5	1	1.15	34	
			1—.5	1	1.15	37	
			.5 & Finer	1	.75	40	
Medium Carbon ASTM A27: Grades N1, N2, U-60-30, 60-30, 65-35, 70-36, 70-40 ASTM A148: Grades 80-40, 80-50, 90-60, 105-85, 120-95, 150-125, 175-145 ASTM A216: Grades WCA, WCB, WCC ASTM A217: Grades WC1, WC4, WC5, WC6 ASTM A352: Grades LC1, LC2, LC2-1 ASTM A356: Grades 2, 5, 6, 8, 9, 10 ASTM A389: Grades C23, C24 ASTM A486: Classes 70, 90, 120 (materials continued on next page)	175 to 225	Annealed, Normalized, or Normalized and Tempered	1—2	2	060	110	M2, M7
			3—10	1	.060	130	
			11—19	1	.060	145	
			20—48	1	.050	155	
			48 & Finer	1	.030	170	
			25—13	2	1.50	34	S4, S2
			12—2.5	1	1.50	40	
			2—1.5	1	1.50	44	
			1—.5	1	1.25	47	
			.5 & Finer	1	.75	52	
	225 to 250	Normalized, Normalized and Tempered or Quenched and Tempered	1—2	2	.060	95	M2, M7
			3—10	1	.060	110	
			11—19	1	.060	125	
			20—48	1	.050	140	
			48 & Finer	1	.030	155	
			25—13	2	1.50	30	S4, S2
			12—2.5	1	1.50	34	
			2—1.5	1	1.50	40	
			1—.5	1	1.25	43	
			.5 & Finer	1	.75	47	

For hobbing Class 9 (per AGMA 390.03) or better gears, it may be necessary to reduce speeds and feeds by 50% and/or take 2 cuts. To meet finish requirements it may be necessary to try both conventional and climb cutting

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*Feeds are based on the largest standard recommended hob diameter. When using a smaller hob diameter, the Feed must be reduced proportionally.

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	NUMBER OF CUTS	FEED* PER REVOLUTION OF WORKPIECE in / mm	HOB SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
16. ALLOY STEELS, CAST (cont.) **Medium Carbon (cont.)** (materials continued from preceding page) ASTM A487· Classes 1N, 2N, 4N, 6N, 8N, 9N, 10N, DN, 1Q, 2Q, 4Q, 4QA, 6Q, 7Q, 8Q, 9Q, 10Q 1330 4130 80B30 8640 1340 4140 8040 9525 2325 4330 8430 9530 2330 4340 8440 9535 4125 8030 8630	250 to 300	Quenched and Tempered	1—2	2	.045	80	M2, M7
			3—10	1	045	90	
			11—19	1	045	105	
			20—48	1	.045	110	
			48 & Finer	1	030	120	
			25—13	2	1.15	24	S4, S2
			12—2.5	1	1.15	27	
			2—1.5	1	1.15	32	
			1—.5	1	1.15	34	
			.5 & Finer	1	.75	37	
	300 to 350	Quenched and Tempered	1—2	2	.045	70	M2, M7
			3—10	1	.045	75	
			11—19	1	045	85	
			20—48	1	.045	90	
			48 & Finer	1	.030	100	
			25—13	2	1.15	21	S4, S2
			12—2.5	1	1.15	23	
			2—1.5	1	1.15	26	
			1—.5	1	1.15	27	
			.5 & Finer	1	.75	30	
	350 to 400	Quenched and Tempered	1—2	2	045	55	M3, M42
			3—10	1	.045	60	
			11—19	1	.025	70	
			20—48	1	.025	75	
			48 & Finer	1	.025	85	
			25—13	2	1.15	17	S5, S11
			12—2.5	1	1.15	18	
			2—1.5	1	.65	21	
			1—.5	1	65	23	
			.5 & Finer	1	66	26	
18. STAINLESS STEELS, CAST **Ferritic** ASTM A217: Grades C5, C12 ASTM A296: Grades CB-30, CC-50, CE-30, CA6N, CA-6NM, CD4MCu ASTM A297: Grade HC ASTM A487: Class CA6NM ASTM A608: Grade HC30	135 to 185	Annealed	1—2	2	.060	120	M2, M7
			3—10	1	.060	130	
			11—19	1	.060	145	
			20—48	1	.050	155	
			48 & Finer	1	.030	165	
			25—13	2	1.50	37	S4, S2
			12—2.5	1	1.50	40	
			2—1.5	1	1.50	44	
			1—.5	1	1.25	47	
			.5 & Finer	1	.75	50	
Austenitic ASTM A296. Grades CF-16F, CN-7M, CN-7MS ASTM A351· Grade CN-7M	140 to 170	Annealed or Normalized	1—2	2	.060	90	M2, M7
			3—10	1	.060	100	
			11—19	1	.060	120	
			20—48	1	.050	130	
			48 & Finer	1	.030	150	
			25—13	2	1.50	27	S4, S2
			12—2.5	1	1.50	30	
			2—1.5	1	1.50	34	
			1—.5	1	1.25	40	
			.5 & Finer	1	.75	46	

For hobbing Class 9 (per AGMA 390.03) or better gears, it may be necessary to reduce speeds and feeds by 50% and/or take 2 cuts. To meet finish requirements it may be necessary to try both conventional and climb cutting

See section 16 for Cutting Fluid Recommendations.

*Feeds are based on the largest standard recommended hob diameter. When using a smaller hob diameter, the Feed must be reduced proportionally.

7.1 Gear Hobbing

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	NUMBER OF CUTS	FEED* PER REVOLUTION OF WORKPIECE :n mm	HOB SPEED fpm m/min	HSS TOOL MATERIAL AISI ISO
18. STAINLESS STEELS, CAST (cont.)			1—2	2	.060	90	
Austenitic			3—10	1	060	100	
ASTM A296 Grades CF-3, CF-8, CF-8C, CF-20	135 to 185	Annealed or Normalized	11—19	1	.060	115	M2, M7
ASTM A351. Grades CF-3, CF-3A, CF-8, CF-8A, CF-8C			20—48	1	050	125	
ASTM A451 Grades CPF3, CPF3A, CPF8, CPF8A, CPF8C, CPF8C (Ta Max)			48 & Finer	1	030	135	
ASTM A452. Grades TP 304H, TP 347H			25—13	2	1.50	27	
			12—2.5	1	1.50	30	
			2—1.5	1	1.50	35	S4, S2
			1—.5	1	1.25	38	
			.5 & Finer	1	.75	41	
Austenitic			1—2	2	060	80	
ASTM A296: Grades CF-3M, CF-8M, CG-8M, CG-12, CH 20, CK-20			3—10	1	060	90	
ASTM A351: Grades CF-3M, CF-3MA, CF-8M, CF-10MC, CH-8, CH-10, CH-20, CK-20, HK-30, HK-40, HT-30	135 to 185	Annealed or Normalized	11—19	1	060	105	M2, M7
ASTM A451 Grades CPF3M, CPF8M, CPF10MC, CPH8, CPH10, CPH20, CPK20			20—48	1	050	115	
ASTM A452. Grade TP 316H			48 & Finer	1	.030	125	
			25—13	2	1.50	24	
			12—2.5	1	1.50	27	
			2—1.5	1	1.50	32	S4, S2
			1—.5	1	1.25	35	
			.5 & Finer	1	.75	38	
Austenitic			1—2	2	.060	75	
ASTM A297: Grades HD, HE, HF, HH, HI, HK HL, HN, HP, HT, HU			3—10	1	.060	85	
			11—19	1	.060	100	M2, M7
ASTM A608: Grades HD50, HE35, HF30, HH30, HH33, HI35, HK30, HK40, HL30, HL40, HN40, HT50, HU50	160 to 210	As Cast	20—48	1	.050	110	
			48 & Finer	1	.030	120	
			25—13	2	1.50	23	
			12—2.5	1	1.50	27	
			2—1.5	1	1.50	30	S4, S2
			1—.5	1	1.25	34	
			.5 & Finer	1	.75	37	
Martensitic			1—2	2	.060	95	
ASTM A217: Grade CA-15			3—10	1	.060	110	
ASTM A296. Grades CA-15, CA-15M, CA-40			11—19	1	.060	125	M2, M7
ASTM A426. Grades CP7, CP9, CPCA15	135 to 175	Annealed	20—48	1	.050	135	
ASTM A487: Classes CA15a, CA-15M			48 & Finer	1	.030	145	
			25—13	2	1.50	29	
			12—2.5	1	1.50	34	
			2—1.5	1	1.50	38	S4, S2
			1—.5	1	1.25	41	
			.5 & Finer	1	.75	44	

For hobbing Class 9 (per AGMA 390.03) or better gears, it may be necessary to reduce speeds and feeds by 50% and/or take 2 cuts. To meet finish requirements it may be necessary to try both conventional and climb cutting.

See section 16 for Cutting Fluid Recommendations.

*Feeds are based on the largest standard recommended hob diameter. When using a smaller hob diameter, the Feed must be reduced proportionally.

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	NUMBER OF CUTS	FEED* PER REVOLUTION OF WORKPIECE in / mm	HOB SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
18. STAINLESS STEELS, CAST (cont.) **Martensitic (cont.)** (materials listed on preceding page)	175 to 225	Annealed, Normalized or Normalized and Tempered	1—2	2	.060	80	M2, M7
			3—10	1	.060	105	
			11—19	1	060	115	
			20—48	1	.050	125	
			48 & Finer	1	030	140	
			25—13	2	1.50	24	S4, S2
			12—2.5	1	1.50	32	
			2—1.5	1	1.50	35	
			1—.5	1	1.25	38	
			.5 & Finer	1	.75	43	
	275 to 325	Quenched and Tempered	1—2	2	.045	50	M2, M7
			3—10	1	.045	70	
			11—19	1	.045	80	
			20—48	1	.045	90	
			48 & Finer	1	.030	105	
			25—13	2	1.15	15	S4, S2
			12—2.5	1	1.15	21	
			2—1.5	1	1.15	24	
			1—.5	1	1.15	27	
			.5 & Finer	1	.75	32	
19. PRECIPITATION HARDENING STAINLESS STEELS, CAST ASTM A351: Grade CD-4MCu ACI Grade CB-7Cu ACI Grade CD-4MCu 17-4 PH AM-355	325 to 375	Solution Treated	1—2	2	.045	45	M3, M42
			3—10	1	045	60	
			11—19	1	.025	70	
			20—48	1	.025	75	
			48 & Finer	1	.025	85	
			25—13	2	1.15	14	S5, S11
			12—2.5	1	1.15	18	
			2—1.5	1	.85	21	
			1—.5	1	.85	23	
			.5 & Finer	1	.65	26	
21. GRAY CAST IRONS **Ferritic** ASTM A48. Class 20 SAE J431c: Grade G1800	120 to 150	Annealed	1—2	1	.060	155	M2, M7
			3—10	1	.050	180	
			11—19	1	.030	210	
			20—48	1	.015	220	
			48 & Finer	1	.015	240	
			25—13	1	1.50	47	S4, S2
			12—2.5	1	1.25	56	
			2—1.5	1	.75	64	
			1—.5	1	.40	67	
			.5 & Finer	1	.40	73	
Pearlitic- Ferritic ASTM A48: Class 25 SAE J431c: Grade G2500	160 to 200	As Cast	1—2	1	.060	100	M2, M7
			3—10	1	.050	110	
			11—19	1	.030	130	
			20—48	1	.015	135	
			48 & Finer	1	.015	150	
			25—13	1	1.50	30	S4, S2
			12—2.5	1	1.25	34	
			2—1.5	1	.75	48	
			1—.5	1	.40	41	
			.5 & Finer	1	.40	46	
Pearlitic ASTM A48: Classes 30, 35, 40 SAE J431c: Grade G3000	190 to 220	As Cast	1—2	1	060	75	M2, M7
			3—10	1	.050	85	
			11—19	1	.030	95	
			20—48	1	.015	110	
			48 & Finer	1	.015	120	
			25—13	1	1.50	26	S4, S2
			12—2.5	1	1.25	29	
			2—1.5	1	.75	39	
			1—.5	1	.40	36	
			.5 & Finer	1	.40	40	

For hobbing Class 9 (per AGMA 390.03) or better gears, it may be necessary to reduce speeds and feeds by 50% and/or take 2 cuts To meet finish requirements it may be necessary to try both conventional and climb cutting.

See section 16 for Cutting Fluid Recommendations

*Feeds are based on the largest standard recommended hob diameter. When using a smaller hob diameter, the Feed must be reduced proportionally.

7.1 Gear Hobbing

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	NUMBER OF CUTS	FEED* PER REVOLUTION OF WORKPIECE in / mm	HOB SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
21. GRAY CAST IRONS (cont.) **Pearlitic + Free Carbides** ASTM A48 Classes 45, 50 SAE J431c: Grades G3500, G4000	220 to 260	As Cast	1—2	2	.060	60	M2, M7
			3—10	1	.050	65	
			11—19	1	.030	75	
			20—48	1	.020	80	
			48 & Finer	1	015	90	
			25—13	2	1.50	18	S4, S2
			12—2.5	1	1.25	20	
			2—1.5	1	.75	23	
			1—.5	1	.50	24	
			.5 & Finer	1	.40	27	
Pearlitic or Acicular + Free Carbides ASTM A48, Classes 55, 60	250 to 320	As Cast or Quenched and Tempered	1—2	2	060	40	M2, M7
			3—10	1	050	45	
			11—19	1	030	55	
			20—48	1	.020	60	
			48 & Finer	1	015	70	
			25—13	2	1.50	12	S4, S2
			12—2.5	1	1.25	14	
			2—1.5	1	.75	17	
			1—.5	1	.50	18	
			.5 & Finer	1	.40	21	
Austenitic (NI-RESIST) ASTM A436 Types 1 1b, 2, 2b, 3, 4, 5, 6	100 to 250	As Cast	1—2	2	.060	50	M2, M7
			3—10	1	.050	55	
			11—19	1	.030	65	
			20—48	1	.020	70	
			48 & Finer	1	.015	80	
			25—13	2	1.50	15	S4, S2
			12—2.5	1	1.25	17	
			2—1.5	1	.75	20	
			1—.5	1	.50	21	
			.5 & Finer	1	.40	24	
23. DUCTILE CAST IRONS **Ferritic** ASTM A536: Grades 60-40-18, 65-45-12 SAE J434c: Grades D4018, D4512	140 to 190	Annealed	1—2	1	060	135	M2, M7
			3—10	1	050	155	
			11—19	1	.030	170	
			20—48	1	.020	185	
			48 & Finer	1	.015	200	
			25—13	1	1.50	41	S4, S2
			12—2.5	1	1.25	47	
			2—1.5	1	.75	52	
			1—.5	1	.50	56	
			.5 & Finer	1	.40	59	
Ferritic- Pearlitic ASTM A536: Grade 80-55-06 SAE J434c: Grade D5506	190 to 225	As Cast	1—2	1	.060	90	M2, M7
			3—10	1	.050	100	
			11—19	1	030	120	
			20—48	1	.020	130	
			48 & Finer	1	.015	140	
			25—13	1	1.50	31	S4, S2
			12—2.5	1	1.25	36	
			2—1.5	1	.75	42	
			1—.5	1	.50	46	
			.5 & Finer	1	.40	49	
	225 to 260	As Cast	1—2	1	.060	75	M2, M7
			3—10	1	.050	95	
			11—19	1	.030	115	
			20—48	1	.020	125	
			48 & Finer	1	.015	135	
			25—13	1	1.50	26	S4, S2
			12—2.5	1	1.25	31	
			2—1.5	1	.75	36	
			1—.5	1	.50	40	
			.5 & Finer	1	.40	43	

For hobbing Class 9 (per AGMA 390.03) or better gears, it may be necessary to reduce speeds and feeds by 50% and/or take 2 cuts. To meet finish requirements it may be necessary to try both conventional and climb cutting.

See section 16 for Cutting Fluid Recommendations.

*Feeds are based on the largest standard recommended hob diameter. When using a smaller hob diameter, the Feed must be reduced proportionally.

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	NUMBER OF CUTS	FEED* PER REVOLUTION OF WORKPIECE in / mm	HOB SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
Pearlitic- Martensitic ASTM A536· Grade 100-70-03 SAE J434c Grade D7003	240 to 300	Normalized and Tempered	1—2	1	.060	60	M2, M7
			3—10	1	050	65	
			11—19	1	030	70	
			20—48	1	.020	80	
			48 & Finer	1	.015	90	
			25—13	1	1.50	18	S4, S2
			12—2.5	1	1.25	20	
			2—1.5	1	.75	21	
			1—.5	1	.50	24	
			.5 & Finer	1	.40	27	
Martensitic ASTM A536· Grade 120-90-02 SAE J434c Grade DQ&T	270 to 330	Quenched and Tempered	1—2	1	.060	35	M2, M7
			3—10	1	.050	50	
			11—19	1	030	60	
			20—48	1	.020	70	
			48 & Finer	1	.015	80	
			25—13	1	1.50	11	S4, S2
			12—2.5	1	1.25	15	
			2—1.5	1	.75	16	
			1—.5	1	.50	21	
			.5 & Finer	1	.40	24	
Austenitic (NI-RESIST Ductile) ASTM A439· Types D-2, D-2C, D-3A, D-5 ASTM A571: Type D-2M	120 to 200	Annealed	1—2	1	035	45	M2, M7
			3—10	1	.030	50	
			11—19	1	.020	60	
			20—48	1	.020	65	
			48 & Finer	1	.015	75	
			25—13	1	.90	14	S4, S2
			12—2.5	1	.75	15	
			2—1.5	1	.50	16	
			1—.5	1	.50	20	
			.5 & Finer	1	.40	23	
Austenitic (NI-RESIST Ductile) ASTM A439: Types D-2B, D-3, D-4, D-5B	140 to 275	Annealed	1—2	1	.035	40	M2, M7
			3—10	1	.030	45	
			11—19	1	.020	55	
			20—48	1	.020	60	
			48 & Finer	1	.015	70	
			25—13	1	.90	12	S4, S2
			12—2.5	1	.75	14	
			2—1.5	1	.50	17	
			1—.5	1	.50	19	
			.5 & Finer	1	.40	21	
24. MALLEABLE CAST IRONS **Ferritic** ASTM A47: Grades 32510, 35018 ASTM A602: Grade M3210 SAE J158: Grade M3210	110 to 160	Malleablized	1—2	1	.060	200	M2, M7
			3—10	1	.050	225	
			11—19	1	.030	260	
			20—48	1	.020	270	
			48 & Finer	1	.015	300	
			25—13	1	1.50	90	S4, S2
			12—2.5	1	1.25	95	
			2—1.5	1	.75	75	
			1—.5	1	.50	80	
			.5 & Finer	1	.40	85	
Pearlitic ASTM A220: Grades 40010, 45006, 45008, 50005 ASTM A602: Grade M4504, M5003 SAE J158: Grades M4504, M5003	160 to 200	Malleablized and Heat Treated	1—2	1	.060	125	M2, M7
			3—10	1	.050	150	
			11—19	1	.030	175	
			20—48	1	.020	180	
			48 & Finer	1	.015	200	
			25—13	1	1.50	60	S4, S2
			12—2.5	1	1.25	65	
			2—1.5	1	.75	70	
			1—.5	1	.50	75	
			.5 & Finer	1	.40	80	

For hobbing Class 9 (per AGMA 390 03) or better gears, it may be necessary to reduce speeds and feeds by 50% and/or take 2 cuts. To meet finish requirements it may be necessary to try both conventional and climb cutting

See section 16 for Cutting Fluid Recommendations.

*Feeds are based on the largest standard recommended hob diameter. When using a smaller hob diameter, the Feed must be reduced proportionally.

7.1 Gear Hobbing

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	NUMBER OF CUTS	FEED* PER REVOLUTION OF WORKPIECE in / mm	HOB SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
24. MALLEABLE CAST IRONS (cont.) **Pearlitic (cont.)** (materials listed on preceding page)	200 to 240	Malleablized and Heat Treated	1—2	1	050	100	M2, M7
			3—10	1	050	120	
			11—19	1	030	140	
			20—48	1	.020	150	
			48 & Finer	1	015	160	
			25—13	1	1.50	30	S4, S2
			12—2.5	1	1.25	37	
			2—1.5	1	.75	43	
			1—.5	1	.50	46	
			.5 & Finer	1	.40	49	
Tempered Martensite ASTM A220: Grade 60004 ASTM A602 Grade M5503 SAE J158. Grade M5503	200 to 255	Malleablized and Heat Treated	1—2	1	.060	90	M2, M7
			3—10	1	.050	110	
			11—19	1	.030	130	
			20—48	1	.020	140	
			48 & Finer	1	.015	150	
			25—13	1	1.50	27	S4, S2
			12—2.5	1	1.25	34	
			2—1.5	1	.75	40	
			1—.5	1	.50	43	
			.5 & Finer	1	.40	46	
Tempered Martensite ASTM A220. Grade 70003 ASTM A602 Grade M7002 SAE J158. Grade M7002	220 to 260	Malleablized and Heat Treated	1—2	1	.060	85	M2, M7
			3—10	1	050	105	
			11—19	1	.030	125	
			20—48	1	.020	135	
			48 & Finer	1	.015	145	
			25—13	1	1.50	26	S4, S2
			12—2.5	1	1.25	32	
			2—1.5	1	.75	38	
			1—.5	1	.50	41	
			.5 & Finer	1	.40	44	
Tempered Martensite ASTM A220. Grade 80002 ASTM A602: Grade M8501 SAE J158: Grade M8501	240 to 280	Malleablized and Heat Treated	1—2	1	.060	80	M2, M7
			3—10	1	.050	100	
			11—19	1	.030	120	
			20—48	1	.020	130	
			48 & Finer	1	.015	140	
			25—13	1	1.50	24	S4, S2
			12—2.5	1	1.25	30	
			2—1.5	1	.75	37	
			1—.5	1	.50	40	
			.5 & Finer	1	.40	43	
Tempered Martensite ASTM A220: Grade 90001 ASTM A602: Grade M8501 SAE J158 Grade M8501	250 to 320	Malleablized and Heat Treated	1—2	1	.060	70	M2, M7
			3—10	1	.050	90	
			11—19	1	.030	110	
			20—48	1	.020	120	
			48 & Finer	1	.015	130	
			25—13	1	1.50	21	S4, S2
			12—2.5	1	1.25	27	
			2—1.5	1	.75	34	
			1—.5	1	.50	37	
			.5 & Finer	1	.40	40	

For hobbing Class 9 (per AGMA 390.03) or better gears, it may be necessary to reduce speeds and feeds by 50% and/or take 2 cuts. To meet finish requirements it may be necessary to try both conventional and climb cutting.

See section 16 for Cutting Fluid Recommendations.

*Feeds are based on the largest standard recommended hob diameter. When using a smaller hob diameter, the Feed must be reduced proportionally.

MATERIAL	HARDNESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	NUMBER OF CUTS	FEED* PER REVOLUTION OF WORKPIECE in / mm	HOB SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
28. ALUMINUM ALLOYS, WROUGHT EC 2218 5252 6253 1060 2219 5254 6262 1100 2618 5454 6463 1145 3003 5456 6951 1175 3004 5457 7001 1235 3005 5652 7004 2011 4032 5657 7005 2014 5005 6053 7039 2017 5050 6061 7049 2018 5052 6063 7050 2021 5056 6066 7075 2024 5083 6070 7079 2025 5086 6101 7175 2117 5154 6151 7178	30 to 80 500kg	Cold Drawn	1—2	1	.060	850	M2, M7
			3—10	1	050	900	
			11—19	1	030	1000	
			20—48	1	020	1050	
			48 & Finer	1	015	1150	
			25—13	1	1.50	200	S4, S2
			12—2.5	1	1.25	275	
			2—1.5	1	.75	305	
			1—.5	1	.50	320	
			.5 & Finer	1	.40	350	
	75 to 150 500kg	Solution Treated and Aged	1—2	1	060	800	M2, M7
			3—10	1	050	850	
			11—19	1	.030	950	
			20—48	1	.020	1000	
			48 & Finer	1	.015	1100	
			25—13	1	1.50	245	S4, S2
			12—2.5	1	1.25	260	
			2—1.5	1	.75	290	
			1—.5	1	.50	305	
			.5 & Finer	1	.40	335	
29. ALUMINUM ALLOYS, CAST Sand and Permanent Mold A140 319.0 357 0 A712.0 201.0 328.0 359.0 D712.0 208 0 A332.0 B443 0 713 0 213.0 F332 0 514.0 771.0 222 0 333.0 A514.0 850.0 224 0 354.0 B514 0 A850 0 242 0 355.0 520 0 B850.0 295 0 C355 0 535.0 B295 0 356 0 705.0 308 0 A356.0 707 0 Hiduminium RR-350	40 to 100 500kg	As Cast	1—2	1	.060	700	M2, M7
			3—10	1	.050	750	
			11—19	1	.030	850	
			20—48	1	.020	900	
			48 & Finer	1	.015	1000	
			25—13	1	1.50	215	S4, S2
			12—2.5	1	1.25	230	
			2—1.5	1	.75	260	
			1—.5	1	.50	275	
			.5 & Finer	1	.40	305	
	70 to 125 500kg	Solution Treated and Aged	1—2	1	.060	700	M2, M7
			3—10	1	050	750	
			11—19	1	.030	850	
			20—48	1	.020	900	
			48 & Finer	1	.015	1000	
			25—13	1	1.50	215	S4, S2
			12—2.5	1	1.25	230	
			2—1.5	1	.75	260	
			1—.5	1	.50	275	
			.5 & Finer	1	.40	305	
34. COPPER ALLOYS, WROUGHT 145 332 360 482 147 335 365 485 173 340 366 544 187 342 367 623 191 349 368 624 314 350 370 638 316 353 377 642 330 356 385 782	10 R_B to 70 R_B	Annealed	1—2	1	.060	600	M2, M7
			3—10	1	.050	650	
			11—19	1	.030	700	
			20—48	1	.020	750	
			48 & Finer	1	.015	800	
			25—13	1	1.50	185	S4, S2
			12—2.5	1	1.25	200	
			2—1.5	1	.75	215	
			1—.5	1	.50	230	
			.5 & Finer	1	.40	245	
	60 R_B to 100 R_B	Cold Drawn	1—2	1	060	650	M2, M7
			3—10	1	.050	700	
			11—19	1	.030	750	
			20—48	1	.020	800	
			48 & Finer	1	.015	850	
			25—13	1	1.50	200	S4, S2
			12—2.5	1	1.25	215	
			2—1.5	1	.75	230	
			1—.5	1	.50	245	
			.5 & Finer	1	.40	260	

For hobbing Class 9 (per AGMA 390 03) or better gears, it may be necessary to reduce speeds and feeds by 50% and/or take 2 cuts. To meet finish requirements it may be necessary to try both conventional and climb cutting.

See section 16 for Cutting Fluid Recommendations.

*Feeds are based on the largest standard recommended hob diameter. When using a smaller hob diameter, the Feed must be reduced proportionally.

7.1 Gear Hobbing

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	NUMBER OF CUTS	FEED* PER REVOLUTION OF WORKPIECE in / mm	HOB SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
34. COPPER ALLOYS, WROUGHT (cont.)							
190 425 466 667 226 435 467 675 230 442 613 687 240 443 618 694 260 444 630 770 268 445 632 270 464 651 280 465 655	10 R_B to 70 R_B	Annealed	1—2	1	060	250	M2, M7
			3—10	1	050	300	
			11—19	1	.030	350	
			20—48	1	.020	400	
			48 & Finer	1	.015	450	
			25—13	1	1.50	75	S4, S2
			12—2.5	1	1.25	90	
			2—1.5	1	.75	105	
			1—.5	1	.50	120	
			.5 & Finer	1	.40	135	
	60 R_B to 100 R_B	Cold Drawn	1—2	1	.060	300	M2, M7
			3—10	1	.050	350	
			11—19	1	.030	400	
			20—48	1	.020	450	
			48 & Finer	1	.015	500	
			25—13	1	1.50	90	S4, S2
			12—2.5	1	1.25	105	
			2—1.5	1	.75	120	
			1—.5	1	.50	135	
			.5 & Finer	1	.40	150	
101 125 185 614 102 127 189 619 104 128 192 625 105 129 194 674 107 130 195 688 109 142 210 706 110 143 220 710 111 150 411 715 113 155 413 725 114 162 505 745 115 165 510 752 116 170 511 754 119 172 521 757 120 175 524 121 182 608 122 184 610	10 R_B to 70 R_B	Annealed	1—2	1	.060	100	M2, M7
			3—10	1	.050	110	
			11—19	1	.030	130	
			20—48	1	.020	135	
			48 & Finer	1	015	150	
			25—13	1	1.50	30	S4, S2
			12—2.5	1	1.25	34	
			2—1.5	1	.75	40	
			1—.5	1	.50	41	
			.5 & Finer	1	.40	46	
	60 R_B to 100 R_B	Cold Drawn	1—2	1	.060	125	M2, M7
			3—10	1	.050	150	
			11—19	1	.030	160	
			20—48	1	.020	180	
			48 & Finer	1	.015	200	
			25—13	1	1.50	36	S4, S2
			12—2.5	1	1.25	46	
			2—1.5	1	.75	49	
			1—.5	1	.50	55	
			.5 & Finer	1	.40	60	
35. COPPER ALLOYS, CAST							
834 855 934 953 836 857 935 954 838 858 937 956 842 864 938 973 844 867 939 974 848 879 943 976 852 928 944 978 854 932 945	40 to 150 500kg	As Cast	1—2	1	.060	600	M2, M7
			3—10	1	.050	700	
			11—19	1	.030	800	
			20—48	1	.020	900	
			48 & Finer	1	.015	950	
			25—13	1	1.50	165	S4, S2
			12—2.5	1	1.25	215	
			2—1.5	1	.75	245	
			1—.5	1	.50	275	
			.5 & Finer	1	.40	290	
817 874 925 821 875 926 833 876 927 853 878 947 861 903 948 862 905 952 865 915 955 868 922 957 872 923 958	40 to 175 500kg	As Cast	1—2	1	.060	250	M2, M7
			3—10	1	.050	300	
			11—19	1	.030	350	
			20—48	1	.020	400	
			48 & Finer	1	.015	450	
			25—13	1	1.50	75	S4, S2
			12—2.5	1	1.25	90	
			2—1.5	1	.75	105	
			1—.5	1	.50	120	
			.5 & Finer	1	.40	135	

For hobbing Class 9 (per AGMA 390 03) or better gears, it may be necessary to reduce speeds and feeds by 50% and/or take 2 cuts
To meet finish requirements it may be necessary to try both conventional and climb cutting

See section 16 for Cutting Fluid Recommendations.
*Feeds are based on the largest standard recommended hob diameter. When using a smaller hob diameter, the Feed must be reduced proportionally.

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	NUMBER OF CUTS	FEED* PER REVOLUTION OF WORKPIECE in / mm	HOB SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
801 815 828 916 803 818 863 917 805 820 902 962 807 822 907 963 809 824 909 964 811 825 910 966 813 826 911 967 814 827 913	40 to 200 500kg	As Cast	1—2	1	.060	100	M2, M7
			3—10	1	050	110	
			11—19	1	030	130	
			20—48	1	020	135	
			48 & Finer	1	.015	150	
			25—13	1	1.50	30	S4, S2
			12—2.5	1	1.25	34	
			2—1.5	1	.75	40	
			1—.5	1	.50	41	
			.5 & Finer	1	.40	46	

For hobbing Class 9 (per AGMA 390.03) or better gears, it may be necessary to reduce speeds and feeds by 50% and/or take 2 cuts. To meet finish requirements it may be necessary to try both conventional and climb cutting

See section 16 for Cutting Fluid Recommendations.
*Feeds are based on the largest standard recommended hob diameter. When using a smaller hob diameter, the Feed must be reduced proportionally.

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Gear Cutting, Straight and Spiral Bevel 7.2

MATERIAL	HARD-NESS Bhn	CONDITION	CUTTING SPEED ROUGHING fpm / m/min	CUTTING SPEED FINISHING fpm / m/min	HSS TOOL MATERIAL AISI / ISO
1. FREE MACHINING CARBON STEELS, WROUGHT **Low Carbon Resulfurized** 1116 1118 1211 1117 1119 1212	100 to 150	Hot Rolled or Annealed	125 38	250 76	M2, M7 S4, S2
	150 to 200	Cold Drawn	140 43	275 84	M2, M7 S4, S2
Low Carbon Resulfurized 1213 1215	100 to 150	Hot Rolled or Annealed	140 43	275 84	M2, M7 S4, S2
	150 to 200	Cold Drawn	145 44	290 88	M2, M7 S4, S2
Low Carbon Resulfurized 1108 1109 1110 1113	100 to 150	Hot Rolled or Annealed	110 34	225 69	M2, M7 S4, S2
	150 to 200	Cold Drawn	125 38	250 76	M2, M7 S4, S2
Medium Carbon Resulfurized 1132 1140 1145 1137 1141 1146 1139 1144 1151	175 to 225	Hot Rolled, Normalized, Annealed or Cold Drawn	85 26	175 53	M2, M7 S4, S2
	275 to 325	Quenched and Tempered	70 21	140 43	M2, M7 S4, S2
	325 to 375	Quenched and Tempered	50 15	100 30	M3 S6
Low Carbon Leaded 10L18 11L17	100 to 150	Hot Rolled, Normalized, Annealed or Cold Drawn	140 43	275 84	M2, M7 S4, S2
	150 to 200	Hot Rolled, Normalized, Annealed or Cold Drawn	130 40	265 81	M2, M7 S4, S2

Cutting speed recommendations are for use with Alternate-Tooth Milling Cutters or Gear Generators.
For Planer-Type Generators use the recommended cutting speeds in section 7 3 Gear Shaping.
See section 16 for Cutting Fluid Recommendations.

7.2 Gear Cutting, Straight and Spiral Bevel

MATERIAL	HARD-NESS Bhn	CONDITION	CUTTING SPEED ROUGHING fpm / m/min	CUTTING SPEED FINISHING fpm / m/min	HSS TOOL MATERIAL AISI / ISO
1. FREE MACHINING CARBON STEELS, WROUGHT (cont.) **Low Carbon Leaded (cont.)** (materials listed on preceding page)	200 to 250	Hot Rolled, Normalized, Annealed or Cold Drawn	110 34	220 67	M2, M7 S4, S2
Low Carbon Leaded 12L13 12L14 12L15	100 to 150	Hot Rolled, Normalized, Annealed or Cold Drawn	145 44	290 88	M2, M7 S4, S2
	150 to 200	Hot Rolled, Normalized, Annealed or Cold Drawn	145 44	290 88	M2, M7 S4, S2
	200 to 250	Hot Rolled, Normalized, Annealed or Cold Drawn	110 34	225 69	M2, M7 S4, S2
Medium Carbon Leaded 10L45 10L50 11L37 11L41 11L44	125 to 175	Hot Rolled, Normalized, Annealed or Cold Drawn	110 34	225 69	M2, M7 S4, S2
	175 to 225	Hot Rolled, Normalized, Annealed or Cold Drawn	100 30	200 60	M2, M7 S4, S2
	225 to 275	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	90 27	175 53	M2, M7 S4, S2
	275 to 325	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	80 24	155 47	M2, M7 S4, S2
	325 to 375	Quenched and Tempered	60 18	110 34	M3 S5
2. CARBON STEELS, WROUGHT **Low Carbon** 1005 1012 1019 1026 1006 1013 1020 1029 1008 1015 1021 1513 1009 1016 1022 1518 1010 1017 1023 1522 1011 1018 1025	85 to 125	Hot Rolled, Normalized, Annealed or Cold Drawn	90 28	190 38	M2, M7 S4, S2
	125 to 175	Hot Rolled, Normalized, Annealed or Cold Drawn	90 28	185 38	M2, M7 S4, S2

Cutting speed recommendations are for use with Alternate-Tooth Milling Cutters or Gear Generators
For Planer-Type Generators use the recommended cutting speeds in section 7.3 Gear Shaping.
See section 16 for Cutting Fluid Recommendations

MATERIAL	HARD-NESS Bhn	CONDITION	CUTTING SPEED ROUGHING fpm / m/min	CUTTING SPEED FINISHING fpm / m/min	HSS TOOL MATERIAL AISI / ISO
2. CARBON STEELS, WROUGHT (cont.) **Low Carbon (cont.)** (materials listed on preceding page)	175 to 225	Hot Rolled Normalized, Annealed or Cold Drawn	80 24	165 50	M2, M7 S4, S2
	225 to 275	Annealed or Cold Drawn	70 21	145 44	M2, M7 S4, S2
Medium Carbon 1030 1042 1053 1541 1033 1043 1055 1547 1035 1044 1524 1548 1037 1045 1525 1551 1038 1046 1526 1552 1039 1049 1527 1040 1050 1536	125 to 175	Hot Rolled, Normalized, Annealed or Cold Drawn	85 26	175 53	M2, M7 S4, S2
	175 to 225	Hot Rolled, Normalized, Annealed or Cold Drawn	75 23	155 47	M2, M7 S4, S2
	225 to 275	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	70 21	145 44	M2, M7 S4, S2
	275 to 325	Hot Rolled, Normalized, Annealed or Quenched and Tempered	60 18	125 38	M2, M7 S4, S2
	325 to 375	Quenched and Tempered	50 15	100 30	M3 S5
High Carbon 1060 1074 1085 1566 1064 1075 1086 1572 1065 1078 1090 1069 1080 1095 1070 1084 1561	175 to 225	Hot Rolled, Normalized, Annealed or Cold Drawn	70 21	145 44	M2, M7 S4, S2
	225 to 275	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	65 20	130 40	M2, M7 S4, S2
	275 to 325	Hot Rolled, Normalized, Annealed or Quenched and Tempered	60 18	120 36	M2, M7 S4, S2
	325 to 375	Quenched and Tempered	45 14	95 29	M3 S5

Cutting speed recommendations are for use with Alternate-Tooth Milling Cutters or Gear Generators.
For Planer-Type Generators use the recommended cutting speeds in section 7.3 Gear Shaping.
See section 16 for Cutting Fluid Recommendations

7.2 Gear Cutting, Straight and Spiral Bevel

MATERIAL	HAR	CONDITION	CUTTING SPEED ROUGHING fpm m/min	CUTTING SPEED FINISHING fpm m/min	HSS TOOL MATERIAL AISI ISO
3. CARBON AND FERRITIC ALLOY STEELS (HIGH TEMPERATURE SERVICE) ASTM A369. Grades FPA, FPB, FP1, FP2, FP12	150 to 200	As Forged	85 / 26	175 / 53	M2, M7 / S4, S2
ASTM A369 Grades FP3b, FP11	100 to 200	Annealed or Normalized and Tempered	75 / 23	150 / 46	M2, M7 / S4, S2
ASTM A369. Grades FP5, FP7, FP9, FP21, FP22	150 to 200	Annealed or Normalized and Tempered	70 / 21	140 / 43	M2, M7 / S4, S2
4. FREE MACHINING ALLOY STEELS, WROUGHT **Medium Carbon Resulfurized** 4140 4142Te 4147Te 4140Se 4145Se 4150	150 to 200	Hot Rolled, Normalized, Annealed or Cold Drawn	85 / 26	175 / 53	M2, M7 / S4, S2
	200 to 250	Hot Rolled, Normalized, Annealed or Cold Drawn	75 / 23	155 / 47	M2, M7 / S4, S2
	275 to 325	Quenched and Tempered	65 / 20	135 / 41	M2, M7 / S4, S2
	325 to 375	Quenched and Tempered	45 / 14	95 / 29	M3 / S5
Medium and High Carbon Leaded 41L30 41L50 86L20 41L40 43L40 86L40 41L45 51L32 41L47 52L100	150 to 200	Hot Rolled, Normalized, Annealed or Cold Drawn	85 / 26	175 / 53	M2, M7 / S4, S2
	200 to 250	Hot Rolled, Normalized, Annealed or Cold Drawn	75 / 23	155 / 47	M2, M7 / S4, S2
	275 to 325	Quenched and Tempered	65 / 20	135 / 41	M2, M7 / S4, S2
	325 to 375	Quenched and Tempered	45 / 14	90 / 27	M3 / S5

Cutting speed recommendations are for use with Alternate-Tooth Milling Cutters or Gear Generators.
For Planer-Type Generators use the recommended cutting speeds in section 7.3 Gear Shaping.
See section 16 for Cutting Fluid Recommendations.

MATERIAL	HARD-NESS Bhn	CONDITION	CUTTING SPEED ROUGHING fpm / m/min	CUTTING SPEED FINISHING fpm / m/min	HSS TOOL MATERIAL AISI / ISO
5. ALLOY STEELS, WROUGHT **Low Carbon** 4012 4615 4817 8617 4023 4617 4820 8620 4024 4620 5015 8622 4118 4621 5115 8822 4320 4718 5120 9310 4419 4720 6118 94B15 4422 4815 6115 94B17	125 to 175	Hot Rolled, Annealed or Cold Drawn	85 26	175 53	M2, M7 S4, S2
	175 to 225	Hot Rolled, Annealed or Cold Drawn	75 23	150 46	M2, M7 S4, S2
	225 to 275	Hot Rolled, Normalized, Annealed or Cold Drawn	65 20	130 40	M2, M7 S4, S2
	275 to 325	Normalized or Quenched and Tempered	60 18	120 37	M2, M7 S4, S2
	325 to 375	Normalized or Quenched and Tempered	50 15	100 30	M3 S5
Medium Carbon 1330 4145 5132 8640 1335 4147 5135 8642 1340 4150 5140 8645 1345 4161 5145 86B45 4027 4340 5147 8650 4028 4427 5150 8655 4032 4626 5155 8660 4037 50B40 5160 8740 4042 50B44 51B60 8742 4047 5046 6150 9254 4130 50B46 81B45 9255 4135 50B50 8625 9260 4137 5060 8627 94B30 4140 50B60 8630 4142 5130 8637	175 to 225	Hot Rolled, Annealed or Cold Drawn	65 20	135 41	M2, M7 S4, S2
	225 to 275	Annealed Normalized, Cold Drawn or Quenched and Tempered	60 18	125 38	M2, M7 S4, S2
	275 to 325	Normalized or Quenched and Tempered	55 17	110 34	M2, M7 S4, S2
	325 to 375	Normalized or Quenched and Tempered	50 15	100 30	M3 S5
High Carbon 50100 51100 52100 M-50	175 to 225	Hot Rolled, Annealed or Cold Drawn	60 18	125 38	M2, M7 S4, S2
	225 to 275	Normalized, Cold Drawn or Quenched and Tempered	50 15	100 30	M2, M7 S4, S2

Cutting speed recommendations are for use with Alternate-Tooth Milling Cutters or Gear Generators.
For Planer-Type Generators use the recommended cutting speeds in section 7 3 Gear Shaping.
See section 16 for Cutting Fluid Recommendations

7.2 Gear Cutting, Straight and Spiral Bevel

MATERIAL	HARD-NESS Bhn	CONDITION	CUTTING SPEED ROUGHING fpm / m/min	CUTTING SPEED FINISHING fpm / m/min	HSS TOOL MATERIAL AISI / ISO
5. ALLOY STEELS, WROUGHT (cont.) **High Carbon (cont.)** (materials listed on preceding page)	275 to 325	Normalized or Quenched and Tempered	45 14	90 27	M2, M7 S4, S2
	325 to 375	Normalized or Quenched and Tempered	40 12	80 24	M3 S5
6. HIGH STRENGTH STEELS, WROUGHT 300M 98BV40 4330V D6ac 4340 H11 4340Si H13	225 to 300	Annealed	45 14	90 27	M2, M7 S4, S2
	300 to 350	Normalized	40 12	80 24	M2, M7 S4, S2
HP 9-4-20 HP 9-4-25 HP 9-4-30 HP 9-4-45	325 to 375	Annealed	40 12	80 24	M2, M7 S4, S2
7. MARAGING STEELS, WROUGHT 120 Grade 180 Grade	275 to 325	Annealed	60 18	120 37	M2, M7 S4, S2
ASTM A538 Grades A, B, C 200 Grade 250 Grade 300 Grade 350 Grade HY230	275 to 325	Annealed	50 15	100 30	M2, M7 S4, S2
8. TOOL STEELS, WROUGHT **High Speed** M1 M10 T6 M2 T1 M6 T2	200 to 250	Annealed	50 15	100 30	M2, M7 S4, S2
High Speed M3-1 M33 M43 T5 M3-2 M34 M44 T8 M4 M36 M46 T15 M7 M41 M47 M30 M42 T4	225 to 275	Annealed	45 14	90 27	M2, M7 S4, S2

Cutting speed recommendations are for use with Alternate-Tooth Milling Cutters or Gear Generators
For Planer-Type Generators use the recommended cutting speeds in section 7.3 Gear Shaping.
See section 16 for Cutting Fluid Recommendations.

MATERIAL	HARD-NESS Bhn	CONDITION	CUTTING SPEED ROUGHING fpm / m/min	CUTTING SPEED FINISHING fpm / m/min	HSS TOOL MATERIAL AISI / ISO
Hot Work H10 H19 H25 H11 H21 H26 H12 H22 H42 H13 H23 H14 H24	150 to 200	Annealed	80 24	160 49	M2, M7 S4, S2
	200 to 250	Annealed	65 20	130 40	M2, M7 S4, S2
	325 to 375	Quenched and Tempered	45 14	95 29	M3 S5
Cold Work A2 A9 D7 A3 A10 O1 A4 D2 O2 A6 D3 O6 A7 D4 O7 A8 D5	200 to 250	Annealed	65 20	130 40	M2, M7 S4, S2
Shock Resisting S1 S6 S2 S7 S5	175 to 225	Annealed	70 21	145 44	M2, M7 S4, S2
Mold P2 P4 P5 P6	100 to 150	Annealed	90 27	180 55	M2, M7 S4, S2
Mold P20 P21	150 to 200	Annealed	80 24	165 50	M2, M7 S4, S2
Special Purpose L2 L6 L7	150 to 200	Annealed	70 21	145 44	M2, M7 S4, S2
Special Purpose F1 F2	200 to 250	Annealed	65 20	135 41	M2, M7 S4, S2
Water Hardening W1, W2, W5 SAE J438b. Types W108, W109, W110, W112, W209, W210, W310	150 to 200	Annealed	90 27	180 55	M2, M7 S4, S2

Cutting speed recommendations are for use with Alternate-Tooth Milling Cutters or Gear Generators.
For Planer-Type Generators use the recommended cutting speeds in section 7.3 Gear Shaping.
See section 16 for Cutting Fluid Recommendations.

7.2 Gear Cutting, Straight and Spiral Bevel

MATERIAL	HARD-NESS Bhn	CONDITION	CUTTING SPEED ROUGHING fpm m/min	CUTTING SPEED FINISHING fpm m/min	HSS TOOL MATERIAL AISI ISO
9. NITRIDING STEELS, WROUGHT Nitralloy 125 Nitralloy 135 Nitralloy 135 Mod Nitralloy 225 Nitralloy 230 Nitralloy EZ Nitralloy N Nitrex 1	200 to 250	Annealed	65 20	130 40	M2, M7 S4, S2
	300 to 350	Normalized or Quenched and Tempered	55 17	110 34	M2, M7 S4, S2
12. FREE MACHINING STAINLESS STEELS, WROUGHT **Ferritic** 430F 430F Se	135 to 185	Annealed	85 26	175 53	M2, M7 S4, S2
Austenitic 203EZ 303Pb 303 303 Plus X 303MA 303Se	135 to 185	Annealed	60 18	150 46	M2, M7 S4, S2
	225 to 275	Cold Drawn	65 20	135 41	M2, M7 S4, S2
Martensitic 416 420F Se 416 Plus X 440F 416Se 440F Se 420F	135 to 185	Annealed	85 26	175 53	M2, M7 S4, S2
	185 to 240	Annealed or Cold Drawn	75 23	155 47	M2, M7 S4, S2
	275 to 325	Quenched and Tempered	60 18	120 37	M2, M7 S4, S2
13. STAINLESS STEELS, WROUGHT **Ferritic** 405 430 442 409 434 446 429 436	135 to 185	Annealed	75 23	150 46	M2, M7 S4, S2
Austenitic 201 304 321 385 202 304L 347 301 305 348 302 308 384	135 to 185	Annealed	60 18	120 37	M2, M7 S4, S2
	225 to 275	Cold Drawn	55 17	110 34	M2, M7 S4, S2

Cutting speed recommendations are for use with Alternate-Tooth Milling Cutters or Gear Generators.
For Planer-Type Generators use the recommended cutting speeds in section 7.3 Gear Shaping.
See section 16 for Cutting Fluid Recommendations

MATERIAL	HARD-NESS Bhn	CONDITION	CUTTING SPEED ROUGHING fpm / m/min	CUTTING SPEED FINISHING fpm / m/min	HSS TOOL MATERIAL AISI / ISO
Austenitic 302B 310S 317 309 314 330 309S 316 310 316L	135 to 185	Annealed	50 15	100 30	M2, M7 S4, S2
	225 to 275	Cold Drawn	45 14	90 27	M2, M7 S4, S2
Austenitic Nitronic 32 Nitronic 50 Nitronic 33 Nitronic 60 Nitronic 40	210 to 250	Annealed	40 12	80 24	M2, M7 S4, S2
Martensitic 403 422 410 501 420 502	135 to 175	Annealed	75 23	150 46	M2, M7 S4, S2
	175 to 225	Annealed	70 21	140 43	M2, M7 S4, S2
	275 to 325	Quenched and Tempered	55 17	110 34	M2, M7 S4, S2
Martensitic 414 431 Greek Ascoloy	225 to 275	Annealed	60 18	120 37	M2, M7 S4, S2
	275 to 325	Quenched and Tempered	55 17	110 34	M2, M7 S4, S2
Martensitic 440A 440B 440C	225 to 275	Annealed	55 17	115 35	M2, M7 S4, S2
	275 to 325	Quenched and Tempered	50 15	105 32	M2, M7 S4, S2

Cutting speed recommendations are for use with Alternate-Tooth Milling Cutters or Gear Generators
For Planer-Type Generators use the recommended cutting speeds in section 7.3 Gear Shaping.
See section 16 for Cutting Fluid Recommendations

7.2 Gear Cutting, Straight and Spiral Bevel

MATERIAL	HARD-NESS Bhn	CONDITION	CUTTING SPEED ROUGHING fpm / m/min	CUTTING SPEED FINISHING fpm / m/min	HSS TOOL MATERIAL AISI / ISO
14. PRECIPITATION HARDENING STAINLESS STEELS, WROUGHT 15-5 PH 16-6 PH 17-4 PH 17-7 PH 17-14 Cu Mo AF-71 AFC-77 Almar 362 (AM-362) AM-350 AM-355 AM-363 Custom 450 Custom 455 HNM PH 13-8 Mo PH 14-8 Mo PH 15-7 Mo Stainless W	150 to 200	Solution Treated	55 17	110 34	M2, M7 S4, S2
	275 to 325	Solution Treated or Hardened	45 14	95 29	M2, M7 S4, S2
	325 to 375	Solution Treated or Hardened	40 12	85 26	M3 S5
15. CARBON STEELS, CAST **Low Carbon** ASTM A426 Grade CP1 1010 1020	100 to 150	Annealed, Normalized or Normalized and Tempered	95 29	190 58	M2, M7 S4, S2
Medium Carbon ASTM A352 Grades LCA, LCB, LCC ASTM A356 Grade 1 1030 1040 1050	125 to 175	Annealed, Normalized or Normalized and Tempered	90 27	185 56	M2, M7 S4, S2
	175 to 225	Annealed, Normalized or Normalized and Tempered	75 23	155 47	M2, M7 S4, S2
	250 to 300	Quenched and Tempered	65 20	135 41	M2, M7 S4, S2
16. ALLOY STEELS, CAST **Low Carbon** ASTM A217 Grade WC9 ASTM A352 Grades LC3, LC4 ASTM A426, Grades CP2, CP5, CP5b, CP11, CP12, CP15, CP21, CP22 1320 2320 4120 8020 2315 4110 4320 8620	150 to 200	Annealed, Normalized or Normalized and Tempered	85 26	170 52	M2, M7 S4, S2
	200 to 225	Annealed, Normalized or Normalized and Tempered	70 21	145 44	M2, M7 S4, S2
	250 to 300	Quenched and Tempered	65 20	130 40	M2, M7 S4, S2

Cutting speed recommendations are for use with Alternate-Tooth Milling Cutters or Gear Generators
For Planer-Type Generators use the recommended cutting speeds in section 7.3 Gear Shaping.
See section 16 for Cutting Fluid Recommendations

MATERIAL	HARD-NESS Bhn	CONDITION	CUTTING SPEED ROUGHING fpm	CUTTING SPEED FINISHING fpm	HSS TOOL MATERIAL AISI ISO
Medium Carbon ASTM A27: Grades N1, N2, U-60-30, 60-30, 65-35, 70-36, 70-40 ASTM A148: Grades 80-40, 80-50, 90-60, 105-85, 120-95, 150-125, 175-145 ASTM A216: Grades WCA, WCB, WCC ASTM A217: Grades WC1, WC4, WC5, WC6 ASTM A352: Grades LC1, LC2, LC2-1 ASTM A356: Grades 2, 5, 6, 8, 9, 10 ASTM A389: Grades C23, C24 ASTM A486: Classes 70, 90, 120 ASTM A487: Classes 1N, 2N, 4N, 6N, 8N, 9N, 10N, DN, 1Q, 2Q, 4Q, 4QA, 6Q, 7Q, 8Q, 9Q, 10Q 1330 4130 80B30 8640 1340 4140 8040 9525 2325 4330 8430 9530 2330 4340 8440 9535 4125 8030 8630	175 to 225	Annealed, Normalized, or Normalized and Tempered	70	145	M2, M7
			21	44	S4, S2
	225 to 250	Normalized, Normalized and Tempered or Quenched and Tempered	65	135	M2, M7
			20	41	S4, S2
	250 to 300	Quenched and Tempered	65	130	M2, M7
			20	40	S4, S2
	300 to 350	Quenched and Tempered	55	115	M2, M7
			17	35	S4, S2
	350 to 400	Quenched and Tempered	50	100	M42, M3
			15	30	S11, S5
18. STAINLESS STEELS, CAST **Ferritic** ASTM A217: Grades C5, C12 ASTM A296: Grades CB-30, CC-50, CE-30, CA6N, CA-6NM, CD4MCu ASTM A297: Grade HC ASTM A487: Class CA6NM ASTM A608: Grade HC30	135 to 185	Annealed	75	150	M2, M7
			23	45	S4, S2
Austenitic ASTM A296: Grades CF-16F, CN-7M, CN-7MS ASTM A351: Grade CN-7M	140 to 170	Annealed or Normalized	70	145	M2, M7
			21	44	S4, S2
Austenitic ASTM A296: Grades CF-3, CF-8, CF-8C, CF-20 ASTM A351: Grades CF-3, CF-3A, CF-8, CF-8A, CF-8C ASTM A451: Grades CPF3, CPF3A, CPF8, CPF8A, CPF8C, CPF8C (Ta Max) ASTM A452: Grades TP 304H, TP 347H	135 to 185	Annealed or Normalized	60	120	M2, M7
			18	37	S4, S2

Cutting speed recommendations are for use with Alternate-Tooth Milling Cutters or Gear Generators.
For Planer-Type Generators use the recommended cutting speeds in section 7.3 Gear Shaping.
See section 16 for Cutting Fluid Recommendations.

7.2 Gear Cutting, Straight and Spiral Bevel

MATERIAL	HARD-NESS Bhn	CONDITION	CUTTING SPEED ROUGHING fpm m/min	CUTTING SPEED FINISHING fpm m/min	HSS TOOL MATERIAL AISI ISO
18. STAINLESS STEELS, CAST (cont.) **Austenitic** ASTM A296. Grades CF-3M, CF-8M, CG-8M, CG-12, CH-20, CK-20 ASTM A351 Grades CF-3M, CF-3MA, CF-8M, CF-10MC, CH-8, CH-10, CH-20, CK-20, HK-30, HK-40, HT-30 ASTM A451 Grades CPF3M, CPF8M, CPF10MC, CPH8, CPH10, CPH20, CPK20 ASTM A452 Grade TP 316H	135 to 185	Annealed or Normalized	50 15	100 30	M2, M7 S4, S2
Austenitic ASTM A297 Grades HD, HE, HF, HH, HI, HK, HL, HN, HP, HT, HU ASTM A608 Grades HD50, HE35, HF30, HH30, HH33, HI35, HK30, HK40, HL30, HL40, HN40, HT50, HU50	160 to 210	As Cast	50 15	100 30	M2 M7 S4, S2
Martensitic ASTM A217 Grade CA-15 ASTM A296. Grades CA-15, CA-15M, CA-40 ASTM A426: Grades CP7, CP9, CPCA15 ASTM A487 Classes CA15a, CA-15M	135 to 175	Annealed	70 21	145 44	M2, M7 S4, S2
	175 to 225	Annealed Normalized or Normalized and Tempered	65 20	135 41	M2, M7 S4, S2
	275 to 325	Quenched and Tempered	50 15	105 32	M2, M7 S4, S2
19. PRECIPITATION HARDENING STAINLESS STEELS, CAST ASTM A351: Grade CD-4MCu ACI Grade CB-7Cu ACI Grade CD-4MCu 17-4 PH AM-355	325 to 375	Solution Treated	35 11	75 23	M3 S5
21. GRAY CAST IRONS **Ferritic** ASTM A48: Class 20 SAE J431c: Grade G1800	120 to 150	Annealed	90 27	185 56	M2, M7 S4, S2
Pearlitic- Ferritic ASTM A48: Class 25 SAE J431c: Grade G2500	160 to 200	As Cast	75 23	150 46	M2, M7 S4, S2

Cutting speed recommendations are for use with Alternate-Tooth Milling Cutters or Gear Generators.
For Planer-Type Generators use the recommended cutting speeds in section 7.3 Gear Shaping.
See section 16 for Cutting Fluid Recommendations.

MATERIAL	HARD-NESS Bhn	CONDITION	CUTTING SPEED ROUGHING fpm / m/min	CUTTING SPEED FINISHING fpm / m/min	HSS TOOL MATERIAL AISI / ISO
Pearlitic ASTM A48 Classes 30, 35, 40 SAE J431c Grade G3000	190 to 220	As Cast	60 18	120 37	M2, M7 S4, S2
Pearlitic + Free Carbides ASTM A48 Classes 45, 50 SAE J431c Grades G3500, G4000	220 to 260	As Cast	50 15	100 30	M2, M7 S4, S2
Pearlitic or Acicular + Free Carbides ASTM A48 Classes 55, 60	250 to 320	As Cast or Quenched and Tempered	40 12	80 24	M2, M7 S4, S2
Austenitic (NI-RESIST) ASTM A436 Types 1, 1b, 2, 2b, 3, 4, 5, 6	100 to 250	As Cast	40 12	85 26	M2, M7 S4, S2
23. DUCTILE CAST IRONS **Ferritic** ASTM A536 Grades 60-40-18, 65-45-12 SAE J434c Grades D4018, D4512	140 to 190	Annealed	80 24	160 49	M2, M7 S4, S2
Ferritic- Pearlitic ASTM A536 Grade 80-55-06 SAE J434c, Grade D5506	190 to 225	As Cast	70 21	140 43	M2, M7 S4, S2
	225 to 260	As Cast	65 20	130 40	M2, M7 S4, S2
Pearlitic- Martensitic ASTM A536 Grade 100-70-03 SAE J434c, Grade D7003	240 to 300	Normalized and Tempered	60 18	125 38	M2, M7 S4, S2
Martensitic ASTM A536: Grade 120-90-02 SAE J434c Grade DQ&T	270 to 330	Quenched and Tempered	60 18	120 37	M2, M7 S4, S2
Austenitic (NI-RESIST Ductile) ASTM A439, Types D-2, D-2C, D-3A, D-5 ASTM A571, Type D-2M	120 to 200	Annealed	35 11	75 23	M2, M7 S4, S2
Austenitic (NI-RESIST Ductile) ASTM A439 Types D-2B, D-3, D-4, D-5B	140 to 275	Annealed	35 11	70 21	M2, M7 S4, S2

Cutting speed recommendations are for use with Alternate-Tooth Milling Cutters or Gear Generators
For Planer-Type Generators use the recommended cutting speeds in section 7.3 Gear Shaping.
See section 16 for Cutting Fluid Recommendations

7.2 Gear Cutting, Straight and Spiral Bevel

MATERIAL	HARD-NESS Bhn	CONDITION	CUTTING SPEED ROUGHING fpm / m/min	CUTTING SPEED FINISHING fpm / m/min	HSS TOOL MATERIAL AISI / ISO
24. MALLEABLE CAST IRONS **Ferritic** ASTM A47 Grades 32510, 35018 ASTM A602 Grade M3210 SAE J158 Grade M3210	110 to 160	Malleablized	90 27	180 55	M2, M7 S4, S2
Pearlitic ASTM A220 Grades 40010, 45006, 45008, 50005 ASTM A602 Grade M4504, M5003 SAE J158 Grades M4504, M5003	160 to 200	Malleablized and Heat Treated	75 23	155 47	M2, M7 S4, S2
	200 to 240	Malleablized and Heat Treated	70 21	145 44	M2, M7 S4, S2
Tempered Martensite ASTM A220 Grade 60004 ASTM A602 Grade M5503 SAE J158 Grade M5503	200 to 255	Malleablized and Heat Treated	65 20	130 40	M2, M7 S4, S2
Tempered Martensite ASTM A220, Grade 70003 ASTM A602 Grade M7002 SAE J158 Grade M7002	220 to 260	Malleablized and Heat Treated	60 18	125 38	M2, M7 S4, S2
Tempered Martensite ASTM A220, Grade 80002 ASTM A602 Grade M8501 SAE J158, Grade M8501	240 to 280	Malleablized and Heat Treated	60 18	120 37	M2, M7 S4, S2
Tempered Martensite ASTM A220 Grade 90001 ASTM A602 Grade M8501 SAE J158 Grade M8501	250 to 320	Malleablized and Heat Treated	55 17	110 34	M2, M7 S4, S2
28. ALUMINUM ALLOYS, WROUGHT EC 2218 5252 6253 1060 2219 5254 6262 1100 2618 5454 6463 1145 3003 5456 6951 1175 3004 5457 7001 1235 3005 5652 7004 2011 4032 5657 7005 2014 5005 6053 7039 2017 5050 6061 7049 2018 5052 6063 7050 2021 5056 6066 7075 2024 5083 6070 7079 2025 5086 6101 7175 2117 5154 6151 7178	30 to 80 500kg	Cold Drawn	145 44	290 88	M2, M7 S4, S2
	75 to 150 500kg	Solution Treated and Aged	145 44	275 84	M2, M7 S4, S2

Cutting speed recommendations are for use with Alternate-Tooth Milling Cutters or Gear Generators.
For Planer-Type Generators use the recommended cutting speeds in section 7.3 Gear Shaping
See section 16 for Cutting Fluid Recommendations.

MATERIAL	HARD-NESS Bhn	CONDITION	CUTTING SPEED ROUGHING fpm m/min	CUTTING SPEED FINISHING fpm m/min	HSS TOOL MATERIAL AISI ISO
29. ALUMINUM ALLOYS, CAST Sand and Permanent Mold A140 319.0 357.0 A712.0 201.0 328.0 359.0 D712.0 208.0 A332.0 B443.0 713.0 213.0 F332.0 514.0 771.0 222.0 333.0 A514.0 850.0 224.0 354.0 B514.0 A850.0 242.0 355.0 520.0 B850.0 295.0 C355.0 535.0 B295.0 356.0 705.0 308.0 A356.0 707.0 Hiduminium RR-350	40 to 100 500kg	As Cast	125 38	250 76	M2, M7 S4, S2
	70 to 125 500kg	Solution Treated and Aged	125 38	250 76	M2, M7 S4, S2
34. COPPER ALLOYS, WROUGHT 145 332 360 482 147 335 365 485 173 340 366 544 187 342 367 623 191 349 368 624 314 350 370 638 316 353 377 642 330 356 385 782	10 R_B to 70 R_B	Annealed	140 43	285 87	M2, M7 S4, S2
	60 R_B to 100 R_B	Cold Drawn	155 47	310 95	M2, M7 S4, S2
190 425 466 667 226 435 467 675 230 442 613 687 240 443 618 694 260 444 630 770 268 445 632 270 464 651 280 465 655	10 R_B to 70 R_B	Annealed	115 35	230 70	M2, M7 S4, S2
	60 R_B to 100 R_B	Cold Drawn	125 38	255 78	M2, M7 S4, S2
101 125 185 614 102 127 189 619 104 128 192 625 105 129 194 674 107 130 195 688 109 142 210 706 110 143 220 710 111 150 411 715 113 155 413 725 114 162 505 745 115 165 510 752 116 170 511 754 119 172 521 757 120 175 524 121 182 608 122 184 610	10 R_B to 70 R_B	Annealed	100 30	200 60	M2, M7 S4, S2
	60 R_B to 100 R_B	Cold Drawn	105 32	215 66	M2, M7 S4, S2

Cutting speed recommendations are for use with Alternate-Tooth Milling Cutters or Gear Generators.
For Planer-Type Generators use the recommended cutting speeds in section 7.3 Gear Shaping
See section 16 for Cutting Fluid Recommendations

7.2 Gear Cutting, Straight and Spiral Bevel

MATERIAL	HARD-NESS Bhn	CONDITION	CUTTING SPEED ROUGHING fpm (m/min)	CUTTING SPEED FINISHING fpm (m/min)	HSS TOOL MATERIAL AISI ISO
35. COPPER ALLOYS, CAST					
834 855 934 953 836 857 935 954 838 858 937 956 842 864 938 973 844 867 939 974 848 879 943 976 852 928 944 978 854 932 945	40 to 150 500kg	As Cast	125 (38)	250 (76)	M2, M7 (S4, S2)
817 868 905 947 821 872 915 948 833 874 922 952 853 875 923 955 861 876 925 957 862 878 926 958 865 903 927	40 to 175 500kg	As Cast	100 (30)	200 (60)	M2, M7 (S4, S2)
801 815 828 916 803 818 863 917 805 820 902 962 807 822 907 963 809 824 909 964 811 825 910 966 813 826 911 993 814 827 913	40 to 200 500kg	As Cast	85 (25)	175 (53)	M2, M7 (S4, S2)

Cutting speed recommendations are for use with Alternate-Tooth Milling Cutters or Gear Generators.
For Planer-Type Generators use the recommended cutting speeds in section 7.3 Gear Shaping.
See section 16 for Cutting Fluid Recommendations.

MATERIAL	HARD-NESS Bhn	CONDITION	NUMBER OF CUTS	DIAMETRAL PITCH / MODULE	ROTARY FEED per cutter stroke (4" P.D. cutter) in / mm	CUTTER SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
1. FREE MACHINING CARBON STEELS, WROUGHT **Low Carbon Resulfurized** 1116 1119 1117 1211 1118 1212	1[illegible] to 150	Hot Rolled or Annealed	4	1—4	.022	85	M2, M7
			2	5—10	016		
			2	11—19	.011		
			2	20—48	.008		
			4	25—6	.55	26	S4, S2
			2	5.5—2.5	.40		
			2	2—1.5	.28		
			2	1—.5	.20		
	150 to 200	Cold Drawn	4	1—4	.022	90	M2, M7
			2	5—10	.016		
			2	11—19	.011		
			2	20—48	.008		
			4	25—6	.55	27	S4, S2
			2	5.5—2.5	.40		
			2	2—1.5	.28		
			2	1—.5	.20		
Low Carbon Resulfurized 1213 1215	100 to 150	Hot Rolled or Annealed	4	1—4	.022	100	M2, M7
			2	5—10	016		
			2	11—19	.011		
			2	20—48	.008		
			4	25—6	.55	30	S4, S2
			2	5.5—2.5	.40		
			2	2—1.5	.28		
			2	1—.5	.20		
	150 to 200	Cold Drawn	4	1—4	.022	110	M2, M7
			2	5—10	.016		
			2	11—19	.011		
			2	20—48	.008		
			4	25—6	.55	34	S4, S2
			2	5.5—2.5	.40		
			2	2—1.5	.28		
			2	1—.5	.20		
Low Carbon Resulfurized 1108 1109 1110 1115	100 to 150	Hot Rolled or Annealed	4	1—4	.022	80	M2, M7
			2	5—10	.016		
			2	11—19	.011		
			2	20—48	.008		
			4	25—6	.55	24	S4, S2
			2	5.5—2.5	.40		
			2	2—1.5	.28		
			2	1—.5	.20		
	150 to 200	Cold Drawn	4	1—4	.022	85	M2, M7
			2	5—10	.016		
			2	11—19	011		
			2	20—48	.008		
			4	25—6	.55	26	S4, S2
			2	5.5—2.5	.40		
			2	2—1.5	.28		
			2	1—.5	.20		
Medium Carbon Resulfurized 1132 1144 1137 1145 1139 1146 1140 1151 1141	175 to 225	Hot Rolled, Normalized, Annealed or Cold Drawn	4	1—4	.022	80	M2, M7
			2	5—10	.016		
			2	11—19	.011		
			2	20—48	.008		
			4	25—6	.55	24	S4, S2
			2	5.5—2.5	.40		
			2	2—1.5	.28		
			2	1—.5	.20		
	275 to 325	Quenched and Tempered	4	1—4	.018	55	M2, M7
			2	5—10	.012		
			2	11—19	.010		
			2	20—48	.008		
			4	25—6	.45	17	S4, S2
			2	5.5—2.5	.36		
			2	2—1.5	.26		
			2	1—.5	.20		

For cutting gears of Class 9 (AGMA 390.03) or better, the Rotary Feed should be reduced and the number of cuts should be increased.
See section 16 for Cutting Fluid Recommendations

7.3 Gear Shaping

MATERIAL	HARD-NESS Bhn	CONDITION	NUMBER OF CUTS	DIAMETRAL PITCH / MODULE	ROTARY FEED per cutter stroke (4" P.D. cutter) in / mm	CUTTER SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
1. FREE MACHINING CARBON STEELS, WROUGHT (cont.) **Medium Carbon Resulfurized (cont.)** (materials listed on preceding page)	325 to 375	Quenched and Tempered	4 2 2 2 4 2 2 2	1—4 5—10 11—19 20—48 25—6 5.5—2.5 2—1.5 1—.5	.012 .010 008 008 .030 .025 .020 .020	40 12	M3, M42 S5/S11
Low Carbon Leaded 10L18 11L17	100 to 150	Hot Rolled, Normalized, Annealed or Cold Drawn	4 2 2 2 4 2 2 2	1—4 5—10 11—19 20—48 25—6 5.5—2.5 2—1.5 1—.5	022 .016 .011 .008 .55 .40 .28 .20	110 34	M2, M7 S4, S2
	150 to 200	Hot Rolled, Normalized, Annealed or Cold Drawn	4 2 2 2 4 2 2 2	1—4 5—10 11—19 20—48 25—6 5.5—2.5 2—1.5 1—.5	.022 016 .011 .008 .55 .40 .28 .20	100 30	M2, M7 S4, S2
	200 to 250	Hot Rolled, Normalized, Annealed or Cold Drawn	4 2 2 2 4 2 2 2	1—4 5—10 11—19 20—48 25—6 5.5—2.5 2—1.5 1—.5	.022 .016 .011 .008 .55 .40 .28 .20	85 26	M2, M7 S4, S2
Low Carbon Leaded 12L13 12L14 12L15	100 to 150	Hot Rolled, Normalized, Annealed or Cold Drawn	4 2 2 2 4 2 2 2	1—4 5—10 11—19 20—48 25—6 5.5—2.5 2—1.5 1—.5	.022 .016 011 .008 .55 .40 .28 .20	125 38	M2, M7 S4, S2
	150 to 200	Hot Rolled, Normalized, Annealed or Cold Drawn	4 2 2 2 4 2 2 2	1—4 5—10 11—19 20—48 25—6 5.5—2.5 2—1.5 1—.5	.022 016 .011 .008 .55 .40 .28 .20	130 40	M2, M7 S4, S2
	200 to 250	Hot Rolled, Normalized, Annealed or Cold Drawn	4 2 2 2 4 2 2 2	1—4 5—10 11—19 20—48 25—6 5.5—2.5 2—1.5 1—.5	.022 .016 .011 .008 .55 .40 .28 .20	90 27	M2, M7 S4, S2
Medium Carbon Leaded 10L45 10L50 11L37 11L41 11L44	125 to 175	Hot Rolled, Normalized, Annealed or Cold Drawn	4 2 2 2 4 2 2 2	1—4 5—10 11—19 20—48 25—6 5.5—2.5 2—1.5 1—.5	022 .016 .011 .008 .55 .40 .28 .20	90 27	M2, M7 S4, S2

For cutting gears of Class 9 (AGMA 390 03) or better, the Rotary Feed should be reduced and the number of cuts should be increased
See section 16 for Cutting Fluid Recommendations.

MATERIAL	HARD-NESS Bhn	CONDITION	NUMBER OF CUTS	DIAMETRAL PITCH / MODULE	ROTARY FEED per cutter stroke (4" P.D. cutter) in / mm	CUTTER SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
1. FREE MACHINING CARBON STEELS, WROUGHT (cont.) **Medium Carbon Leaded (cont.)** (materials listed on preceding page)	175 to 225	Hot Rolled, Normalized, Annealed or Cold Drawn	4 2 2 2	1—4 5—10 11—19 20—48	.022 .016 .011 .008	85	M2, M7
			4 2 2 2	.25—6 5.5—2.5 2—1.5 1—.5	.55 .40 .28 .20	26	S4, S2
	225 to 275	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	4 2 2 2	1—4 5—10 11—19 20—48	022 016 011 008	75	M2, M7
			4 2 2 2	.25—6 5.5—2.5 2—1.5 1—.5	.55 .40 .28 .20	23	S4, S2
	275 to 325	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	4 2 2 2	1—4 5—10 11—19 20—48	.018 .012 010 008	60	M2, M7
			4 2 2 2	.25—6 5.5—2.5 2—1.5 1—.5	.45 .30 .25 .20	18	S4, S2
	325 to 375	Quenched and Tempered	4 2 2 2	1—4 5—10 11—19 20—48	.012 .010 .008 .008	55	M3, M42
			4 2 2 2	.25—6 5.5—2.5 2—1.5 1—.5	.30 .25 .20 .20	17	S5, S11
2. CARBON STEELS, WROUGHT **Low Carbon** 1005 1015 1023 1006 1016 1025 1008 1017 1026 1009 1018 1029 1010 1019 1513 1011 1020 1518 1012 1021 1522 1013 1022	85 to 125	Hot Rolled, Normalized, Annealed or Cold Drawn	4 2 2 2	1—4 5—10 11—19 20—48	.018 .012 .010 .008	90	M2, M7
			4 2 2 2	.25—6 5.5—2.5 2—1.5 1—.5	.45 .30 .25 .20	27	S4, S2
	125 to 175	Hot Rolled, Normalized, Annealed or Cold Drawn	4 2 2 2	1—4 5—10 11—19 20—48	018 .012 .010 .008	80	M2, M7
			4 2 2 2	.25—6 5.5—2.5 2—1.5 1—.5	.45 .30 .25 .20	24	S4, S2
	175 to 225	Hot Rolled, Normalized, Annealed or Cold Drawn	4 2 2 2	1—4 5—10 11—19 20—48	.018 012 .010 .008	70	M2, M7
			4 2 2 2	.25—6 5.5—2.5 2—1.5 1—.5	.45 .30 .25 .20	21	S4, S2
	225 to 275	Annealed or Cold Drawn	4 2 2 2	1—4 5—10 11—19 20—48	.016 .012 .010 .008	60	M2, M7
			4 2 2 2	.25—6 5.5—2.5 2—1.5 1—.5	.40 .30 .25 .20	18	S4, S2

For cutting gears of Class 9 (AGMA 390 03) or better, the Rotary Feed should be reduced and the number of cuts should be increased.
See section 16 for Cutting Fluid Recommendations.

7.3 Gear Shaping

MATERIAL	HARD-NESS Bhn	CONDITION	NUMBER OF CUTS	DIAMETRAL PITCH / MODULE	ROTARY FEED per cutter stroke (4" P.D. cutter) in / mm	CUTTER SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
2. CARBON STEELS, WROUGHT (cont.) **Medium Carbon** 1030 1044 1526; 1033 1045 1527; 1035 1046 1536; 1037 1049 1541; 1038 1050 1547; 1039 1053 1548; 1040 1055 1551; 1042 1524 1552; 1043 1525	125 to 175	Hot Rolled, Normalized, Annealed or Cold Drawn	4	1—4	.018	75	M2, M7
			2	5—10	.012		
			2	11—19	.010		
			2	20—48	.008		
			4	25—6	.45	23	S4, S2
			2	5.5—2.5	.30		
			2	2—1.5	.25		
			2	1—.5	.20		
	175 to 225	Hot Rolled, Normalized, Annealed or Cold Drawn	4	1—4	.018	65	M2, M7
			2	5—10	.012		
			2	11—19	.010		
			2	20—48	.008		
			4	25—6	.45	20	S4, S2
			2	5.5—2.5	.30		
			2	2—1.5	.25		
			2	1—.5	.20		
	225 to 275	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	4	1—4	.016	60	M2, M7
			2	5—10	.012		
			2	11—19	.010		
			2	20—48	.008		
			4	25—6	.40	18	S4, S2
			2	5.5—2.5	.30		
			2	2—1.5	.25		
			2	1—.5	.20		
	275 to 325	Hot Rolled, Normalized, Annealed or Quenched and Tempered	4	1—4	.016	50	M2, M7
			2	5—10	.012		
			2	11—19	.010		
			2	20—48	.008		
			4	25—6	.40	15	S4, S2
			2	5.5—2.5	.30		
			2	2—1.5	.25		
			2	1—.5	.20		
	325 to 375	Quenched and Tempered	4	1—4	.012	40	M3, M42
			2	5—10	.010		
			2	11—19	.008		
			2	20—48	.008		
			4	25—6	.30	12	S6, S11
			2	5.5—2.5	.25		
			2	2—1.5	.20		
			2	1—.5	.20		
High Carbon 1060 1075 1090; 1064 1078 1095; 1065 1080 1561; 1069 1084 1566; 1070 1085 1572; 1074 1086	175 to 225	Hot Rolled, Normalized, Annealed or Cold Drawn	4	1—4	018	65	M2, M7
			2	5—10	.012		
			2	11—19	.010		
			2	20—48	.008		
			4	25—6	.45	20	S4, S2
			2	5.5—2.5	.30		
			2	2—1.5	.25		
			2	1—.5	.20		
	225 to 275	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	4	1—4	.016	55	M2, M7
			2	5—10	.012		
			2	11—19	.010		
			2	20—48	.008		
			4	25—6	.40	17	S4, S2
			2	5.5—2.5	.30		
			2	2—1.5	.25		
			2	1—.5	.20		
	275 to 325	Hot Rolled, Normalized, Annealed or Quenched and Tempered	4	1—4	.016	45	M2, M7
			2	5—10	.012		
			2	11—19	.010		
			2	20—48	.008		
			4	25—6	.40	14	S4, S2
			2	5.5—2.5	.30		
			2	2—1.5	.25		
			2	1—.5	.20		

For cutting gears of Class 9 (AGMA 390 03) or better, the Rotary Feed should be reduced and the number of cuts should be increased
See section 16 for Cutting Fluid Recommendations

MATERIAL	HARD-NESS Bhn	CONDITION	NUMBER OF CUTS	DIAMETRAL PITCH / MODULE	ROTARY FEED per cutter stroke (4" P.D. cutter) in / mm	CUTTER SPEED fpm / m/min	HSS TOCL MATERIAL AISI / ISO
2. CARBON STEELS, WROUGHT (cont.) High Carbon (cont.) (materials listed on preceding page)	325 to 375	Quenched and Tempered	4	1—4	.012	35	M3, M42
			2	5—10	.010		
			2	11—19	.008		
			2	20—48	.008		
			4	25—6	.30	11	S5, S11
			2	5.5—2.5	.25		
			2	2—1.5	.20		
			2	1—.5	.20		
3. CARBON AND FERRITIC ALLOY STEELS (HIGH TEMPERATURE SERVICE) ASTM A369. Grades FPA, FPB, FP1, FP2, FP12	150 to 200	As Forged	4	1—4	.018	60	M2, M7
			2	5—10	.012		
			2	11—19	.010		
			2	20—48	.008		
			4	25—6	.45	18	S4, S2
			2	5.5—2.5	.30		
			2	2—1.5	.25		
			2	1—.5	.20		
ASTM A369 Grades FP3b, FP11	150 to 200	Annealed or Normalized and Tempered	4	1—4	.018	55	M2, M7
			2	5—10	012		
			2	11—19	.010		
			2	20—48	.008		
			4	25—6	.45	17	S4, S2
			2	5.5—2.5	.30		
			2	2—1.5	.25		
			2	1—.5	.20		
ASTM A369. Grades FP5, FP7, FP9, FP21, FP22	150 to 200	Annealed or Normalized and Tempered	4	1—4	.018	50	M2, M7
			2	5—10	.012		
			2	11—19	.010		
			2	20—48	.008		
			4	25—6	.45	15	S4, S2
			2	5.5—2.5	.30		
			2	2—1.5	.25		
			2	1—.5	.20		
4. FREE MACHINING ALLOY STEELS, WROUGHT Medium Carbon Resulfurized 4140 4145Se 4140Se 4147Te 4142Te 4150	150 to 200	Hot Rolled, Normalized, Annealed or Cold Drawn	4	1—4	.022	80	M2, M7
			2	5—10	.018		
			2	11—19	.011		
			2	20—48	.008		
			4	25—6	.55	24	S4, S2
			2	5.5—2.5	.45		
			2	2—1.5	.28		
			2	1—.5	.20		
	200 to 250	Hot Rolled, Normalized, Annealed or Cold Drawn	4	1—4	.022	75	M2, M7
			2	5—10	.018		
			2	11—19	.011		
			2	20—48	.008		
			4	25—6	.55	23	S4, S2
			2	5.5—2.5	.45		
			2	2—1.5	.28		
			2	1—.5	.20		
	275 to 325	Quenched and Tempered	4	1—4	018	50	M2, M7
			2	5—10	.012		
			2	11—19	010		
			2	20—48	.008		
			4	25—6	.45	15	S4, S2
			2	5.5—2.5	.30		
			2	2—1.5	.25		
			2	1—.5	.20		
	325 to 375	Quenched and Tempered	4	1—4	.012	35	M3, M42
			2	5—10	.010		
			2	11—19	.008		
			2	20—48	.008		
			4	25—6	.30	11	S5, S11
			2	5.5—2.5	.25		
			2	2—1.5	.20		
			2	1—.5	.20		

For cutting gears of Class 9 (AGMA 390 03) or better, the Rotary Feed should be reduced and the number of cuts should be increased
See section 16 for Cutting Fluid Recommendations

7.3 Gear Shaping

MATERIAL	HARD-NESS Bhn	CONDITION	NUMBER OF CUTS	DIAMETRAL PITCH / MODULE	ROTARY FEED per cutter stroke (4" P.D. cutter) in / mm	CUTTER SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
4. FREE MACHINING ALLOY STEELS, WROUGHT (cont.) Medium and High Carbon: Leaded 41L30 41L47 51L32 86L40 41L40 41L50 52L100 41L45 43L40 86L20	150 to 200	Hot Rolled, Normalized, Annealed or Cold Drawn	4 2 2 2	1—4 5—10 11—19 20—48	.022 .016 .011 .008	80	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.55 .40 .28 .20	24	S4, S2
	200 to 250	Hot Rolled, Normalized, Annealed or Cold Drawn	4 2 2 2	1—4 5—10 11—19 20—48	.022 .016 .011 .008	75	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.55 .40 .28 .20	23	S4, S2
	275 to 325	Quenched and Tempered	4 2 2 2	1—4 5—10 11—19 20—48	.018 .012 .010 .008	50	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.45 .30 .25 .20	15	S4, S2
	325 to 375	Quenched and Tempered	4 2 2 2	1—4 5—10 11—19 20—48	.012 .010 .008 .008	35	M3, M42
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.30 .25 .20 .20	11	S5, S11
5. ALLOY STEELS, WROUGHT Low Carbon 4012 4615 4817 8617 4023 4617 4820 8620 4024 4620 5015 8622 4118 4621 5115 8822 4320 4718 5120 9310 4419 4720 6118 94B15 4422 4815 8115 94B17	125 to 175	Hot Rolled, Annealed or Cold Drawn	4 2 2 2	1—4 5—10 11—19 20—48	.018 .012 .010 .008	70	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.45 .30 .25 .20	21	S4, S2
	175 to 225	Hot Rolled, Annealed or Cold Drawn	4 2 2 2	1—4 5—10 11—19 20—48	.018 .012 .010 .008	65	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.45 .30 .25 .20	20	S4, S2
	225 to 275	Hot Rolled, Normalized, Annealed or Cold Drawn	4 2 2 2	1—4 5—10 11—19 20—48	.016 .012 .010 .008	50	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.40 .30 .25 .20	15	S4, S2
	275 to 325	Normalized or Quenched and Tempered	4 2 2 2	1—4 5—10 11—19 20—48	.012 .010 008 .008	45	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.30 .25 .20 .20	14	S4, S2

For cutting gears of Class 9 (AGMA 390 03) or better, the Rotary Feed should be reduced and the number of cuts should be increased
See section 16 for Cutting Fluid Recommendations

MATERIAL	HARD-NESS Bhn	CONDITION	NUMBER OF CUTS	DIAMETRAL PITCH / MODULE	ROTARY FEED per cutter stroke (4" P.D. cutter) in / mm	CUTTER SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
5. ALLOY STEELS, WROUGHT (cont.) **Low Carbon (cont.)** (materials listed on preceding page)	325 to 375	Normalized or Quenched and Tempered	4 2 2 2	1—4 5—10 11—19 20—48	012 .010 .008 008	40	M3, M42
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.30 .25 .20 .20	12	S5, S11
Medium Carbon 1330 4427 81B45 1335 4626 8625 1340 50B40 8627 1345 50B44 8630 4027 5046 8637 4028 50B46 8640 4032 50B50 8642 4037 5060 8645 4042 50B60 86B45 4047 5130 8650 4130 5132 8655 4135 5135 8660 4137 5140 8740 4140 5145 8742 4142 5147 9254 4145 5150 9255 4147 5155 9260 4150 5160 94B30 4161 51B60 4340 6150	175 to 225	Hot Rolled, Annealed or Cold Drawn	4 2 2 2	1—4 5—10 11—19 20—48	.018 .012 .010 008	60	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.45 .30 .25 .20	18	S4, S2
	225 to 275	Annealed, Normalized, Cold Drawn or Quenched and Tempered	4 2 2 2	1—4 5—10 11—19 20—48	.016 012 .010 .008	45	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.40 .30 .25 .20	14	S4, S2
	275 to 325	Normalized or Quenched and Tempered	4 2 2 2	1—4 5—10 11—19 20—48	.016 012 .010 .008	40	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.40 .30 .25 .20	12	S4, S2
	325 to 375	Normalized or Quenched and Tempered	4 2 2 2	1—4 5—10 11—19 20—4	.012 .010 .008 .008	35	M3, M42
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.30 .25 .20 .20	11	S5, S11
High Carbon 50100 51100 52100 M-50	175 to 225	Hot Rolled, Annealed or Cold Drawn	4 2 2 2	1—4 5—10 11—19 20—48	.018 .012 .010 .008	55	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.45 .30 .25 .20	17	S4, S2
	225 to 275	Normalized, Cold Drawn or Quenched and Tempered	4 2 2 2	1—4 5—10 11—19 20—48	.016 .012 .010 .008	40	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.40 .30 .25 .20	12	S4, S2
	275 to 325	Normalized or Quenched and Tempered	4 2 2 2	1—4 5—10 11—19 20—48	.016 .012 .010 .008	35	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.40 .30 .25 .20	11	S4, S2

For cutting gears of Class 9 (AGMA 390 03) or better, the Rotary Feed should be reduced and the number of cuts should be increased
See section 16 for Cutting Fluid Recommendations.

7.3 Gear Shaping

MATERIAL	HARD-NESS Bhn	CONDITION	NUMBER OF CUTS	DIAMETRAL PITCH / MODULE	ROTARY FEED per cutter stroke (4" P.D. cutter) in / mm	CUTTER SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
5. ALLOY STEELS, WROUGHT (cont.) **High Carbon (cont.)** (materials listed on preceding page)	325 to 375	Normalized or Quenched and Tempered	4 2 2 2	1—4 5—10 11—19 20—48	.012 .010 .008 .008	30	M3, M42
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.30 .25 .20 .20	9	S5, S11
6. HIGH STRENGTH STEELS, WROUGHT 300M 98BV40 4330V D6ac 4340 H11 4340Si H13	225 to 300	Annealed	4 2 2 2	1—4 5—10 11—19 20—48	.016 .012 .010 .008	45	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.40 .30 .25 .20	14	S4, S2
	300 to 350	Normalized	4 2 2 2	1—4 5—10 11—19 20—48	.012 .010 .008 .008	40	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.30 .25 .20 .20	12	S4, S2
HP 9-4-20 HP 9-4-25 HP 9-4-30 HP 9-4-45	325 to 375	Annealed	4 2 2 2	1—4 5—10 11—19 20—48	.012 .010 .008 .008	45	M3, M42
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.30 .25 .20 .20	14	S5, S11
7. MARAGING STEELS, WROUGHT 120 Grade 180 Grade	275 to 325	Annealed	4 2 2 2	1—4 5—10 11—19 20—48	.012 .010 .008 .008	45	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.30 .25 .20 .20	14	S4, S2
ASTM A538: Grades A B, C 200 Grade 250 Grade 300 Grade 350 Grade HY230	275 to 325	Annealed	4 2 2 2	1—4 5—10 11—19 20—48	.012 .010 .008 .008	35	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.30 .25 .20 .20	11	S4, S2
8. TOOL STEELS, WROUGHT **High Speed** M1 T1 M2 T2 M6 T6 M10	200 to 250	Annealed	4 2 2 2	1—4 5—10 11—19 20—48	.012 .011 .009 .006	30	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.30 .25 .23 .15	9	S4, S2
High Speed M3-1 M34 M46 M3-2 M36 M47 M4 M41 T4 M7 M42 T5 M30 M43 T8 M33 M44 T15	225 to 275	Annealed	4 2 2 2	1—4 5—10 11—19 20—48	.012 .011 .009 .006	20	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.30 .25 .20 .15	6	S4, S2

For cutting gears of Class 9 (AGMA 390.03) or better, the Rotary Feed should be reduced and the number of cuts should be increased
See section 16 for Cutting Fluid Recommendations

MATERIAL	HARD-NESS Bhn	CONDITION	NUMBER OF CUTS	DIAMETRAL PITCH / MODULE	ROTARY FEED per cutter stroke (4" P.D. cutter) in / mm	CUTTER SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
Hot Work H10 H11 H12 H13 H14 H19 H21 H22 H23 H24 H25 H26 H42	150 to 200	Annealed	4 2 2 2	1—4 5—10 11—19 20—48	.018 .015 .010 .008	50	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.45 .40 .25 .20	15	S4, S2
	200 to 250	Annealed	4 2 2 2	1—4 5—10 11—19 20—48	.016 .012 .010 .008	35	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.40 .30 .25 .20	11	S4, S2
	325 to 375	Quenched and Tempered	4 2 2 2	1—4 5—10 11—19 20—48	.012 .010 .008 .006	25	M3, M42
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.30 .25 .20 .15	8	S5, S11
Cold Work A2 D3 A3 D4 A4 D5 A6 D7 A7 O1 A8 O2 A9 O6 A10 O7 D2	200 to 250	Annealed	4 2 2 2	1—4 5—10 11—19 20—48	.016 .012 .010 .008	35	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.40 .30 .25 .20	11	S4, S2
Shock Resisting S1 S2 S5 S6 S7	175 to 225	Annealed	4 2 2 2	1—4 5—10 11—19 20—48	.018 .015 .010 .008	50	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.45 .40 .25 .20	15	S4, S2
Mold P2 P4 P5 P6	100 to 150	Annealed	4 2 2 2	1—4 5—10 11—19 20—48	.018 .015 .010 .008	60	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.45 .40 .25 .20	15	S4, S2
Mold P20 P21	150 to 200	Annealed	4 2 2 2	1—4 5—10 11—19 20—48	.018 .015 .010 .008	50	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.45 .40 .25 .20	15	S4, S2

For cutting gears of Class 9 (AGMA 390 03) or better, the Rotary Feed should be reduced and the number of cuts should be increased
See section 16 for Cutting Fluid Recommendations.

7.3 Gear Shaping

MATERIAL	HARD-NESS Bhn	CONDITION	NUMBER OF CUTS	DIAMETRAL PITCH	ROTARY FEED per cutter stroke (4" P.D. cutter) in	CUTTER SPEED fpm	HSS TOOL MATERIAL AISI
8. TOOL STEELS, WROUGHT (cont.)							
Special Purpose			4	1—4	.018		
L2	150		2	5—10	.015	45	M2, M7
L6	to	Annealed	2	11—19	.010		
L7	200		2	20—48	.008		
			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Special Purpose			4	1—4	.016		
F1	200		2	5—10	.012	35	M2, M7
F2	to	Annealed	2	11—19	.010		
	250		2	20—48	.008		
			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Water Hardening			4	1—4	.018		
W1, W2, W5			2	5—10	.015	60	M2, M7
SAE J438b: Types W108, W109, W110, W112, W209, W210, W310	150 to 200	Annealed	2	11—19	.010		
			2	20—48	.008		
			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
9. NITRIDING STEELS, WROUGHT			4	1—4	.016		
Nitralloy 125			2	5—10	.012	40	M2, M7
Nitralloy 135	200		2	11—19	.010		
Nitralloy 135 Mod.	to	Annealed	2	20—48	.008		
Nitralloy 225	250		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Nitralloy 230							
Nitralloy EZ							
Nitralloy N							
Nitrex 1			4	1—4	.012		
			2	5—10	.012	25	M2, M7
	300	Normalized or Quenched and Tempered	2	11—19	.010		
	to		2	20—48	.008		
	350		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
12. FREE MACHINING STAINLESS STEELS, WROUGHT			4	1—4	.020		
Ferritic			2	5—10	.015	60	M2, M7
430F	135		2	11—19	.010		
430F Se	to	Annealed	2	20—48	.008		
	185		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Austenitic			4	1—4	.020		
203EZ			2	5—10	.015	40	M2, M7
303	135		2	11—19	.010		
303MA	to	Annealed	2	20—48	.008		
303Pb	185		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
303 Plus X							
303Se							
			4	1—4	.020		
			2	5—10	.015	30	M2, M7
	225	Cold Drawn	2	11—19	.010		
	to		2	20—48	.008		
	275		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

For cutting gears of Class 9 (AGMA 390.03) or better, the Rotary Feed should be reduced and the number of cuts should be increased.
See section 16 for Cutting Fluid Recommendations.

MATERIAL	HARD-NESS Bhn	CONDITION	NUMBER OF CUTS	DIAMETRAL PITCH / MODULE	ROTARY FEED per cutter stroke (4" P.D. cutter) in / mm	CUTTER SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
Martensitic 416 420F Se 416 Plus X 440F 416Se 440F Se 420F	135 to 185	Annealed	4 2 2 2	1—4 5—10 11—19 20—48	.020 .015 .010 .008	60	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.50 .40 .25 .20	18	S4, S2
	185 to 240	Annealed or Cold Drawn	4 2 2 2	1—4 5—10 11—19 20—48	.020 .015 .010 .008	50	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.50 .40 .25 .20	15	S4, S2
	275 to 325	Quenched and Tempered	4 2 2 2	1—4 5—10 11—19 20—48	.016 .012 .010 .008	25	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.40 .30 .25 .20	8	S4, S2
13. STAINLESS STEELS, WROUGHT **Ferritic** 405 434 409 436 429 442 430 446	135 to 185	Annealed	4 2 2 2	1—4 5—10 11—19 20—48	.020 .015 .010 .008	40	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.50 .40 .25 .20	12	S4, S2
Austenitic 201 304L 348 202 305 384 301 308 385 302 321 304 347	135 to 185	Annealed	4 2 2 2	1—4 5—10 11—19 20—48	.020 .015 .010 .008	30	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.50 .40 .25 .20	9	S4, S2
	225 to 275	Cold Drawn	4 2 2 2	1—4 5—10 11—19 20—48	.020 .015 .010 .008	25	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.50 .40 .25 .20	6	S4, S2
Austenitic 302B 314 309 316 309S 316L 310 317 310S 330	135 to 185	Annealed	4 2 2 2	1—4 5—10 11—19 20—48	.020 .015 .010 .008	30	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.50 .40 .25 .20	9	S4, S2
	225 to 275	Cold Drawn	4 2 2 2	1—4 5—10 11—19 20—48	.020 .015 .010 .008	20	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.50 .40 .25 .20	6	S4, S2

For cutting gears of Class 9 (AGMA 390.03) or better, the Rotary Feed should be reduced and the number of cuts should be increased
See section 16 for Cutting Fluid Recommendations.

7.3 Gear Shaping

MATERIAL	HARD NESS Bhn	CONDITION	NUMBER OF CUTS	DIAMETRAL PITCH / MODULE	ROTARY FEED per cutter stroke (4" P.D. cutter) in / m.	CUTTER SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
13. STAINLESS STEELS, WROUGHT (cont.)							
Austenitic							
Nitronic 32 Nitronic 50	210 to 250	Annealed	4	1—4	020	20	M2, M7
Nitronic 33 Nitronic 60			2	5—10	015		
Nitronic 40			2	11—19	.010		
			2	20—48	.008		
			4	25—6	.50	6	S4, S2
			2	5.5—2.5	.40		
			2	2—1.5	.25		
			2	1—.5	.20		
Martensitic							
403	135 to 175	Annealed	4	1—4	.020	40	M2, M7
410			2	5—10	.015		
420			2	11—19	.010		
422			2	20—48	.008		
501			4	25—6	.50	12	S4, S2
502			2	5.5—2.5	.40		
			2	2—1.5	.25		
			2	1—.5	.20		
	175 to 225	Annealed	4	1—4	020	35	M2, M7
			2	5—10	015		
			2	11—19	.010		
			2	20—48	.008		
			4	25—6	.50	11	S4, S2
			2	5.5—2.5	.40		
			2	2—1.5	.25		
			2	1—.5	.20		
	275 to 325	Quenched and Tempered	4	1—4	.016	20	M2, M7
			2	5—10	.012		
			2	11—19	.010		
			2	20—48	.008		
			4	25—6	.40	6	S4, S2
			2	5.5—2.5	.30		
			2	2—1.5	.25		
			2	1—.5	.20		
Martensitic							
414	225 to 275	Annealed	4	1—4	.018	30	M2, M7
431			2	5—10	.012		
Greek Ascoloy			2	11—19	.010		
			2	20—48	.008		
			4	25—6	.45	9	S4, S2
			2	5.5—2.5	.30		
			2	2—1.5	.25		
			2	1—.5	.20		
	275 to 325	Quenched and Tempered	4	1—4	.016	20	M2, M7
			2	5—10	.012		
			2	11—19	.010		
			2	20—48	.008		
			4	25—6	.40	6	S4, S2
			2	5.5—2.5	.30		
			2	2—1.5	.25		
			2	1—.5	.20		
Martensitic							
440A	225 to 275	Annealed	4	1—4	.018	30	M2, M7
440B			2	5—10	.012		
440C			2	11—19	.010		
			2	20—48	.008		
			4	25—6	.45	9	S4, S2
			2	5.5—2.5	.30		
			2	2—1.5	.25		
			2	1—.5	.20		
	275 to 325	Quenched and Tempered	4	1—4	.016	20	M2, M7
			2	5—10	.012		
			2	11—19	.010		
			2	20—48	.008		
			4	25—6	.40	6	S4, S2
			2	5.5—2.5	.30		
			2	2—1.5	.25		
			2	1—.5	.20		

For cutting gears of Class 9 (AGMA 390 03) or better, the Rotary Feed should be reduced and the number of cuts should be increased
See section 16 for Cutting Fluid Recommendations.

MATERIAL	HARD-NESS Bhn	CONDITION	NUMBER OF CUTS	DIAMETRAL PITCH / MODULE	ROTARY FEED per cutter stroke (4" P.D. cutter) in / mm	CUTTER SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
14. PRECIPITATION HARDENING STAINLESS STEELS, WROUGHT 15-5 PH 16-6 PH 17-4 PH 17-7 PH 17-14 Cu Mo AF-71 AFC-77 Almar 362 (AM-362) AM-350 AM-355 AM-363 Custom 450 Custom 455 HNM PH 13-8 Mo PH 14-8 Mo PH 15-7 Mo Stainless W	150 to 200	Solution Treated	4 2 2 2	1—4 5—10 11—19 20—48	.018 .012 .010 .008	35	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.45 .30 .25 .20	11	S4, S2
	275 to 325	Solution Treated or Hardened	4 2 2 2	1—4 5—10 11—19 20—48	018 .012 .010 008	25	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.45 .30 .25 .20	8	S4, S2
	325 to 375	Solution Treated or Hardened	4 2 2 2	1—4 5—10 1—19 20—48	.016 .012 010 .008	20	M3, M42
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.40 .30 .25 .20	6	S5, S11
15. CARBON STEELS, CAST **Low Carbon** ASTM A426. Grade CP1 1010 1020	100 to 150	Annealed, Normalized or Normalized and Tempered	4 2 2 2	1—4 5—10 11—19 20—48	018 .012 .010 008	80	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.45 .30 .25 .20	24	S4, S2
Medium Carbon ASTM A352. Grades LCA, LCB, LCC ASTM A356. Grade 1 1030 1040 1050	125 to 175	Annealed, Normalized or Normalized and Tempered	4 2 2 2	1—4 5—10 11—19 20—48	.018 .012 010 .008	75	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.45 .30 .25 .20	23	S4, S2
	175 to 225	Annealed, Normalized or Normalized and Tempered	4 2 2 2	1—4 5—10 11—19 20—48	018 .012 .010 .008	70	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.45 .30 .25 .20	21	S4, S2
	250 to 300	Quenched and Tempered	4 2 2 2	1—4 5—10 11—19 20—48	.016 .012 .010 008	55	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.40 .30 .25 .20	17	S4, S2

For cutting gears of Class 9 (AGMA 390 03) or better, the Rotary Feed should be reduced and the number of cuts should be increased
See section 16 for Cutting Fluid Recommendations.

7.3 Gear Shaping

MATERIAL	HARD-NESS Bhn	CONDITION	NUMBER OF CUTS	DIAMETRAL PITCH / MODULE	ROTARY FEED per cutter stroke (4" P.D. cutter) in / mm	CUTTER SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
16. ALLOY STEELS, CAST							
Low Carbon							
ASTM A217: Grade WC9	150 to 200	Annealed, Normalized or Normalized and Tempered	4	1—4	018	65	M2, M7
ASTM A352: Grades LC3, LC4			2	5—10	.012		
ASTM A426: Grades CP2, CP5, CP5b, CP11, CP12, CP15, CP21, CP22			2	11—19	010		
1320 2320 4120 8020			2	20—48	008		
2315 4110 4320 8620			4	25—6	.45	20	S4, S2
			2	5.5—2.5	.30		
			2	2—1.5	.25		
			2	1—.5	.20		
	200 to 225	Annealed, Normalized or Normalized and Tempered	4	1—4	.018	60	M2, M7
			2	5—10	012		
			2	11—19	.010		
			2	20—48	.008		
			4	25—6	.45	18	S4, S2
			2	5.5—2.5	.30		
			2	2—1.5	.25		
			2	1—.5	.20		
	250 to 300	Quenched and Tempered	4	1—4	.016	50	M2, M7
			2	5—10	012		
			2	11—19	.010		
			2	20—48	.008		
			4	25—6	.40	15	S4, S2
			2	5.5—2.5	.30		
			2	2—1.5	.25		
			2	1—.5	.20		
Medium Carbon							
ASTM A27: Grades N1, N2, U-60-30, 60-30, 65-35, 70-36, 70-40	175 to 225	Annealed, Normalized or Normalized and Tempered	4	1—4	018	55	M2, M7
ASTM A148: Grades 80-40, 80-50, 90-60, 105-85, 120-95, 150-125, 175-145			2	5—10	.012		
ASTM A216: Grades WCA, WCB, WCC			2	11—19	.010		
ASTM A217: Grades WC1, WC4, WC5, WC6			2	20—48	.008		
ASTM A352: Grades LC1, LC2, LC2-1			4	25—6	.45	17	S4, S2
ASTM A356 Grades 2, 5, 6, 8, 9, 10			2	5.5—2.5	.30		
ASTM A389 Grades C23, C24			2	2—1.5	.25		
ASTM A486 Classes 70, 90, 120			2	1—.5	.20		
ASTM A487: Classes 1N, 2N, 4N, 6N, 8N, 9N, 10N, DN, 1Q, 2Q, 4Q, 4QA, 6Q, 7Q, 8Q, 9Q, 10Q	225 to 250	Normalized, Normalized and Tempered or Quenched and Tempered	4	1—4	.016	45	M2, M7
1330 4130 80B30 8640			2	5—10	.012		
1340 4140 8040 9525			2	11—19	.010		
2325 4330 8430 9530			2	20—48	.008		
2330 4340 8440 9535			4	25—6	.40	14	S4, S2
4125 8030 8630			2	5.5—2.5	.30		
			2	2—1.5	.25		
			2	1—.5	.20		
	250 to 300	Quenched and Tempered	4	1—4	.016	40	M2, M7
			2	5—10	.012		
			2	11—19	.010		
			2	20—48	.008		
			4	25—6	.40	12	S4, S2
			2	5.5—2.5	.30		
			2	2—1.5	.25		
			2	1—.5	.20		
	300 to 350	Quenched and Tempered	4	1—4	014	35	M2, M7
			2	5—10	.012		
			2	11—19	010		
			2	20—48	.008		
			4	25—6	.36	11	S4, S2
			2	5.5—2.5	.30		
			2	2—1.5	.25		
			2	1—.5	.20		
	350 to 400	Quenched and Tempered	4	1—4	.012	30	M3, M42
			2	5—10	.010		
			2	11—19	.008		
			2	20—48	.008		
			4	25—6	.30	9	S5, S11
			2	5.5—2.5	.25		
			2	2—1.5	.20		
			2	1—.5	.20		

For cutting gears of Class 9 (AGMA 390 03) or better, the Rotary Feed should be reduced and the number of cuts should be increased.
See section 16 for Cutting Fluid Recommendations

MATERIAL	HARD-NESS Bhn	CONDITION	NUMBER OF CUTS	DIAMETRAL PITCH	ROTARY FEED per cutter stroke (4" P.D. cutter) in mm	CUTTER SPEED fpm m/min	HSS TOOL MATERIAL AISI ISO
18. STAINLESS STEELS, CAST							
Ferritic							
ASTM A217: Grades C5, C12 ASTM A296: Grades CB-30, CC-50, CE-30, CA6N, CA-6NM, CD4MCu ASTM A297: Grade HC ASTM A487: Class CA6NM ASTM A608: Grade HC30	135 to 185	Annealed	4 2 2 2	1—4 5—10 11—19 20—48	.020 .015 .010 .008	40	M2, M7
			[illegible]	[illegible]	[illegible]	12	[illegible]
Austenitic			4 2 2 2	1—4 5—10 11—19 20—48	.018 .012 .010 .008	35	M2, M7
ASTM A296. Grades CF-16F, CN-7M, CN-7MS ASTM A351: Grade CN-7M	140 to 170	Annealed or Normalized	[illegible]	[illegible]	[illegible]	11	[illegible]
Austenitic			4 2 2 2	1—4 5—10 11—19 20—48	.018 .012 .010 .008	30	M2, M7
ASTM A296. Grades CF-3, CF-8, CF-8C, CF-20 ASTM A351: Grades CF-3, CF-3A, CF-8, CF-8A, CF-8C ASTM A451: Grades CPF3, CPF3A, CPF8, CPF8A, CPF8C, CPF8C (Ta Max) ASTM A452: Grades TP 304H, TP 347H	135 to 185	Annealed or Normalized	[illegible]	[illegible]	[illegible]	9	[illegible]
Austenitic			4 2 2 2	1—4 5—10 11—19 20—48	.018 .015 .010 .008	30	M2, M7
ASTM A296: Grades CF-3M, CF-8M, CG-8M, CG-12, CH-20, CK-20 ASTM A351: Grades CF-3M, CF-3MA, CF-8M, CF-10MC, CH-8, CH-10, CH-20, CK-20, HK-30, HK-40, HT-30 ASTM A451: Grades CPF3M, CPF8M, CPF10MC, CPH8, CPH10, CPH20, CPK20 ASTM A452: Grade TP 316H	135 to 185	Annealed or Normalized	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

For cutting gears of Class 9 (AGMA 390 03) or better, the Rotary Feed should be reduced and the number of cuts should be increased.
See section 16 for Cutting Fluid Recommendations.

7.3 Gear Shaping

MATERIAL	HARD-NESS Bhn	CONDITION	NUMBER OF CUTS	DIAMETRAL PITCH / MODULE	ROTARY FEED per cutter stroke (4" P.D. cutter) in / mm	CUTTER SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
18. STAINLESS STEELS, CAST (cont.)							
Austenitic							
ASTM A297: Grades HD, HE, HF, HH, HI, HK, HL, HN, HP, HT, HU	160 to 210	As Cast	4	1—4	.018	30	M2, M7
			2	5—10	.012		
			2	11—19	010		
			2	20—48	.008		
			4	25—6	.45	9	S4, S2
			2	5.5—2.5	.30		
			2	2—1.5	.25		
			2	1—.5	.20		
ASTM A608: Grades HD50, HE35, HF30, HH30, HH33, HI35, HK30, HK40, HL30, HL40, HN40, HT50, HU50							
Martensitic							
ASTM A217 Grade CA-15	135 to 175	Annealed	4	1—4	.020	40	M2, M7
ASTM A296 Grades CA-15, CA-15M, CA-40			2	5—10	.015		
ASTM A426 Grades CP7, CP9, CPCA15			2	11—19	.010		
ASTM A487 Classes CA15a, CA-15M			2	20—48	.008		
			4	25—6	.50	12	S4, S2
			2	5.5—2.5	.40		
			2	2—1.5	.25		
			2	1—.5	.20		
	175 to 225	Annealed, Normalized or Normalized and Tempered	4	1—4	.020	35	M2, M7
			2	5—10	.015		
			2	11—19	.010		
			2	20—48	.008		
			4	25—6	.50	11	S4, S2
			2	5.5—2.5	.40		
			2	2—1.5	.25		
			2	1—.5	.20		
	275 to 325	Quenched and Tempered	4	1—4	.016	20	M2, M7
			2	5—10	.012		
			2	11—19	.010		
			2	20—48	.007		
			4	25—6	.40	6	S4, S2
			2	5.5—2.5	.30		
			2	2—1.5	.25		
			2	1—.5	.18		
19. PRECIPITATION HARDENING STAINLESS STEELS, CAST							
ASTM A351: Grade CD-4MCu	325 to 375	Solution Treated	4	1—4	.016	20	M3, M42
ACI Grade CB-7Cu			2	5—10	.012		
ACI Grade CD-4MCu			2	11—19	.010		
17-4 PH			2	20—48	.008		
AM-355			4	25—6	.40	8	S5, S11
			2	5.5—2.5	.30		
			2	2—1.5	.25		
			2	1—.5	.20		
21. GRAY CAST IRONS							
Ferritic							
ASTM A48 Class 20	120 to 150	Annealed	4	1—4	.018	100	M2, M7
SAE J431c. Grade G1800			2	5—10	.012		
			2	11—19	.010		
			2	20—48	.008		
			4	25—6	.45	90	S4, S2
			2	5.5—2.5	.30		
			2	2—1.5	.25		
			2	1—.5	.20		

For cutting gears of Class 9 (AGMA 390.03) or better, the Rotary Feed should be reduced and the number of cuts should be increased.
See section 16 for Cutting Fluid Recommendations

MATERIAL	HARD-NESS Bhn	CONDITION	NUMBER OF CUTS	DIAMETRAL PITCH / MODULE	ROTARY FEED per cutter stroke (4" P.D. cutter) in / mm	CUTTER SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
Pearlitic- Ferritic ASTM A48 Class 25 SAE J431c. Grade G2500	160 to 200	As Cast	4 2 2 2	1—4 5—10 11—19 20—48	018 012 010 008	85	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.45 .30 .25 .20	26	S4, S2
Pearlitic ASTM A48. Classes 30, 35, 40 SAE J431c: Grade G3000	190 to 220	As Cast	4 2 2 2	1—4 5—10 11—19 20—48	.018 012 .010 .008	70	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.45 .30 .25 .20	21	S4, S2
Pearlitic + Free Carbides ASTM A48 Classes 45, 50 SAE J431c. Grades G3500, G4000	220 to 260	As Cast	4 2 2 2	1—4 5—10 11—19 20—48	.018 .012 .010 .008	60	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.45 .30 .25 .20	18	S4, S2
Pearlitic or Acicular + Free Carbides ASTM A48: Classes 55, 60	250 to 320	As Cast or Quenched and Tempered	4 2 2 2	1—4 5—10 11—19 20—48	.012 .010 .008 .008	40	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.30 .25 .20 .20	12	S4, S2
Austenitic (NI-RESIST) ASTM A436 Types 1, 1b, 2, 2b, 3, 4, 5, 6	100 to 250	As Cast	4 2 2 2	1—4 5—10 11—19 20—48	.018 012 010 .008	50	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.45 .30 .25 .20	15	S4, S2
23. DUCTILE CAST IRONS **Ferritic** ASTM A536. Grades 60-40-18, 65-45-12 SAE J434c Grades D4018, D4512	140 to 190	Annealed	4 2 2 2	1—4 5—10 11—19 20—48	.018 .012 .010 .008	100	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.45 .30 .25 .20	30	S4, S2
Ferritic- Pearlitic ASTM A536 Grade 80-55-06 SAE J434c: Grade D5506	190 to 225	As Cast	4 2 2 2	1—4 5—10 11—19 20—48	.018 .012 .010 .008	80	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.45 .30 .25 .20	24	S4, S2
	225 to 260	As Cast	4 2 2 2	1—4 5—10 11—19 20—48	.018 .012 .010 .008	70	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.45 .30 .25 .20	21	S4, S2

For cutting gears of Class 9 (AGMA 390.03) or better, the Rotary Feed should be reduced and the number of cuts should be increased
See section 16 for Cutting Fluid Recommendations

7.3 Gear Shaping

MATERIAL	HARD-NESS Bhn	CONDITION	NUMBER OF CUTS	DIAMETRAL PITCH / MODULE	ROTARY FEED per cutter stroke (4" P.D. cutter) in / mm	CUTTER SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
23. DUCTILE CAST IRONS (cont.) **Pearlitic- Martensitic** ASTM A536: Grade 100-70-03 SAE J434c: Grade D7003	240 to 300	Normalized and Tempered	4 2 2 2	1—4 5—10 11—19 20—48	.016 .012 .010 .008	60	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	40 30 25 20	18	S4, S2
Martensitic ASTM A536 Grade 120-90-02 SAE J434c: Grade DQ&T	270 to 330	Quenched and Tempered	4 2 2 2	1—4 5—10 11—19 20—48	.012 .010 .008 008	45	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	30 25 20 20	14	S4, S2
Austenitic (NI-RESIST Ductile) ASTM A439: Types D-2, D-2C, D-3A, D-5 ASTM A571: Type D-2M	120 to 200	Annealed	4 2 2 2	1—4 5—10 11—19 20—48	.012 .010 008 .008	40	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	30 25 20 20	12	S4, S2
Austenitic (NI-RESIST Ductile) ASTM A439: Types D-2B, D-3, D-4, D-5B	140 to 275	Annealed	4 2 2 2	1—4 5—10 11—19 20—48	.012 .010 .008 .008	35	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	30 25 20 20	11	S4, S2
24. MALLEABLE CAST IRONS Ferritic ASTM A47. Grades 32510, 35018 ASTM A602. Grade M3210 SAE J158: Grade M3210	110 to 160	Malleablized	4 2 2 2	1—4 5—10 11—19 20—48	.018 012 .010 .008	145	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	45 30 25 20	44	S4, S2
Pearlitic ASTM A220: Grades 40010, 45006, 45008, 50005 ASTM A602. Grade M4504, M5003 SAE J158: Grades M4504, M5003	160 to 200	Malleablized and Heat Treated	4 2 2 2	1—4 5—10 11—19 20—48	.018 .012 .010 .008	100	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	45 30 25 20	30	S4, S2
	200 to 240	Malleablized and Heat Treated	4 2 2 2	1—4 5—10 11—19 20—48	018 .012 .010 .008	70	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	45 30 25 20	21	S4, S2
Tempered Martensite ASTM A220: Grade 60004 ASTM A602: Grade M5503 SAE J158: Grade M5503	200 to 255	Malleablized and Heat Treated	4 2 2 2	1—4 5—10 11—19 20—48	.018 .012 .010 .008	65	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	45 30 25 20	26	S4, S2

For cutting gears of Class 9 (AGMA 390 03) or better, the Rotary Feed should be reduced and the number of cuts should be increased
See section 16 for Cutting Fluid Recommendations.

MATERIAL	HARD-NESS Bhn	CONDITION	NUMBER OF CUTS	DIAMETRAL PITCH / MODULE	ROTARY FEED per cutter stroke (4" P.D. cutter) in / mm	CUTTER SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
Tempered Martensite ASTM A220 Grade 70003 ASTM A602: Grade M7002 SAE J158: Grade M7002	220 to 260	Malleablized and Heat Treated	4 2 2 2	1—4 5—10 11—19 20—48	018 012 010 .008	60	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.45 .30 .25 .20	18	S4, S2
Tempered Martensite ASTM A220: Grade 80002 ASTM A602: Grade M8501 SAE J158 Grade M8501	240 to 280	Malleablized and Heat Treated	4 2 2 2	1—4 5—10 11—19 20—48	016 012 .010 .008	50	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.40 .30 .25 .20	15	S4, S2
Tempered Martensite ASTM A220. Grade 90001 ASTM A602 Grade M8501 SAE J158: Grade M8501	250 to 320	Malleablized and Heat Treated	4 2 2 2	1—4 5—10 11—19 20—48	.012 .010 .008 .008	45	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.30 .25 .20 .20	14	S4, S2
28. ALUMINUM ALLOYS, WROUGHT EC 2218 5252 6253 1060 2219 5254 6262 1100 2618 5454 6463 1145 3003 5456 6951 1175 3004 5457 7001 1235 3005 5652 7004 2011 4032 5657 7005 2014 5005 6053 7039 2017 5050 6061 7049 2018 5052 6063 7050 2021 5056 6066 7075 2024 5083 6070 7079 2025 5086 6101 7175 2117 5154 6151 7178	30 to 80 500kg	Cold Drawn	4 2 2 2	1—4 5—10 11—19 20—48	.028 .024 .015 .008	200	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.70 .60 .40 .20	60	S4, S2
	75 to 150 500kg	Solution Treated and Aged	4 2 2 2	1—4 5—10 11—19 20—48	.028 .024 .015 .008	180	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.70 .60 .40 .20	65	S4, S2
29. ALUMINUM ALLOYS, CAST **Sand and Permanent Mold** A140 319.0 357.0 A712.0 201.0 328.0 359.0 D712.0 208.0 A332.0 B443.0 713.0 213.0 F332.0 514.0 771.0 222.0 333.0 A514.0 850.0 224.0 354.0 B514.0 A850.0 242.0 355.0 520.0 B850.0 295.0 C355.0 535.0 B295.0 356.0 705.0 308.0 A356.0 707.0 Hiduminium RR-350	40 to 100 500kg	As Cast	4 2 2 2	1—4 5—10 11—19 20—48	.028 .024 .015 .008	180	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.70 .60 .40 .20	55	S4, S2
	70 to 125 500kg	Solution Treated and Aged	4 2 2 2	1—4 5—10 11—19 20—48	.028 .024 .015 .008	160	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.70 .60 .40 .20	45	S4, S2

For cutting gears of Class 9 (AGMA 390 03) or better, the Rotary Feed should be reduced and the number of cuts should be increased
See section 16 for Cutting Fluid Recommendations.

7.3 Gear Shaping

MATERIAL				HARD-NESS Bhn	CONDITION	NUMBER OF CUTS	DIAMETRAL PITCH / MODULE	ROTARY FEED per cutter stroke (4" P.D. cutter) in / mm	CUTTER SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
34. COPPER ALLOYS, WROUGHT										
145	332	360	482	10 R_B to 70 R_B	Annealed	4	1—4	018	100	M2, M7
147	335	365	485			2	5—10	012		
173	340	366	544			2	11—19	.010		
187	342	367	623			2	20—48	.008		
191	349	368	624			4	25—6	.45	30	S4, S2
314	350	370	638			2	5.5—2.5	.30		
316	353	377	642			2	2—1.5	.25		
330	356	385	782			2	1—.5	.20		
				60 R_B to 100 R_B	Cold Drawn	4	1—4	.018	110	M2, M7
						2	5—10	.012		
						2	11—19	.010		
						2	20—48	.008		
						4	25—6	.45	34	S4, S2
						2	5.5—2.5	.30		
						2	2—1.5	.25		
						2	1—.5	.20		
190	425	466	667	10 R_B to 70 R_B	Annealed	4	1—4	016	70	M2, M7
226	435	467	675			2	5—10	.012		
230	442	613	687			2	11—19	.010		
240	443	618	694			2	20—48	008		
260	444	630	770			4	25—6	40	21	S4, S2
268	445	632				2	5.5—2.5	.30		
270	464	651				2	2—1.5	.25		
280	465	655				2	1—.5	.20		
				60 R_B to 100 R_B	Cold Drawn	4	1—4	.016	80	M2, M7
						2	5—10	012		
						2	11—19	.010		
						2	20—48	.008		
						4	25—6	40	24	S4, S2
						2	5.5—2.5	.30		
						2	2—1.5	.25		
						2	1—.5	.20		
101	125	185	614	10 R_B to 70 R_B	Annealed	4	1—4	.012	30	M2, M7
102	127	189	619			2	5—10	.012		
104	128	192	625			2	11—19	.010		
105	129	194	674			2	20—48	.008		
107	130	195	688			4	25—6	30	9	S4, S2
109	142	210	706			2	5.5—2.5	.30		
110	143	220	710			2	2—1.5	.25		
111	150	411	715			2	1—.5	.20		
113	155	413	725							
114	162	505	745							
115	165	510	752							
116	170	511	754							
119	172	521	757							
120	175	524								
121	182	608								
122	184	610								
				60 R_B to 100 R_B	Cold Drawn	4	1—4	.012	40	M2, M7
						2	5—10	.012		
						2	11—19	.010		
						2	20—48	.008		
						4	25—6	30	12	S4, S2
						2	5.5—2.5	.30		
						2	2—1.5	.25		
						2	1—.5	.20		

For cutting gears of Class 9 (AGMA 390 03) or better, the Rotary Feed should be reduced and the number of cuts should be increased
See section 16 for Cutting Fluid Recommendations

MATERIAL	HARD-NESS Bhn	CONDITION	NUMBER OF CUTS	DIAMETRAL PITCH / MODULE	ROTARY FEED per cutter stroke (4" P.D. cutter) in / mm	CUTTER SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
35. COPPER ALLOYS, CAST 834 855 934 953 836 857 935 954 838 858 937 956 842 864 938 973 844 867 939 974 848 879 943 976 852 928 944 978 854 932 945	40 to 150 500kg	As Cast	4 2 2 2	1—4 5—10 11—19 20—48	.018 .012 .010 .008	90	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.45 .30 .25 .20	27	S4, S2
817 868 905 947 821 872 915 948 833 874 922 952 853 875 923 955 861 876 925 957 862 878 926 958 865 903 927	40 to 175 500kg	As Cast	4 2 2 2	1—4 5—10 11—19 20—48	.016 .012 .010 .008	60	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.40 .30 .25 .20	18	S4, S2
801 815 828 916 803 818 863 917 805 820 902 962 807 822 907 963 809 824 909 964 811 825 910 966 813 826 911 993 814 827 913	40 to 200 500kg	As Cast	4 2 2 2	1—4 5—10 11—19 20—48	.012 .012 .010 .008	30	M2, M7
			4 2 2 2	25—6 5.5—2.5 2—1.5 1—.5	.30 .30 .25 .20	9	S4, S2

For cutting gears of Class 9 (AGMA 390 03) or better, the Rotary Feed should be reduced and the number of cuts should be increased
See section 16 for Cutting Fluid Recommendations.

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MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	FEED*† per rev. of gear in / mm	CUTTER PITCH LINE SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
1. FREE MACHINING CARBON STEELS, WROUGHT **Low Carbon Resulfurized** 1116 1119 1117 1211 1118 1212	100 to 150	Hot Rolled or Annealed	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	610	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	185	S4, S2
	150 to 200	Cold Drawn	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	675	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	205	S4, S2
Low Carbon Resulfurized 1213 1215	100 to 150	Hot Rolled or Annealed	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	650	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	200	S4, S2
	150 to 200	Cold Drawn	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	730	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	225	S4, S2
Low Carbon Resulfurized 1108 1109 1110 1115	100 to 150	Hot Rolled or Annealed	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	580	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	175	S4, S2
	150 to 200	Cold Drawn	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	620	M2, M7
			25—6 6—3 3—1.5 1 & Finer	.3 .2 .12 .07	190	S4, S2
Medium Carbon Resulfurized 1132 1144 1137 1145 1139 1146 1140 1151 1141	175 to 225	Hot Rolled, Normalized, Annealed or Cold Drawn	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	500	M2, M7
			25—6 6—3 3—1.5 1 & Finer	.3 .2 .12 .07	155	S4, S2
	275 to 325	Quenched and Tempered	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	350	M2, M7
			25—6 6—3 3—1.5 1 & Finer	.3 .2 .12 .07	110	S4, S2

See section 16 for Cutting Fluid Recommendations

*Feed recommendations apply to CONVENTIONAL (axial-transverse) gear shaving.

†Feeds should be increased 100% for gears shaved by the DIAGONAL (angular-transverse) method.

7.4 Gear Shaving

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	FEED*† per rev. of gear in / mm	CUTTER PITCH LINE SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
1. FREE MACHINING CARBON STEELS, WROUGHT (cont.) **Medium Carbon Resulfurized (cont.)** (materials listed on preceding page)	325 to 375	Quenched and Tempered	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 005 .003 3 2 12 07	275 84	M2, M7 S4, S2
Low Carbon Leaded 10L18 11L17	100 to 150	Hot Rolled, Normalized Annealed or Cold Drawn	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 005 .003 3 2 12 07	650 200	M2, M7 S4, S2
	150 to 200	Hot Rolled, Normalized, Annealed or Cold Drawn	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 3 2 12 07	700 215	M2, M7 S4, S2
	200 to 250	Hot Rolled, Normalized, Annealed or Cold Drawn	1—4 5—10 11—19 20 & Finer 5—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 3 2 12 07	575 175	M2, M7 S4, S2
Low Carbon Leaded 12L13 12L14 12L15	100 to 150	Hot Rolled, Normalized, Annealed or Cold Drawn	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 005 .003 3 2 12 07	700 215	M2, M7 S4, S2
	150 to 200	Hot Rolled, Normalized, Annealed or Cold Drawn	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 3 2 12 07	780 240	M2, M7 S4, S2
	200 to 250	Hot Rolled, Normalized, Annealed or Cold Drawn	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 003 3 2 12 07	600 185	M2, M7 S4, S2
Medium Carbon Leaded 10L45 10L50 11L37 11L41 11L44	25 to 175	Hot Rolled, Normalized, Annealed or Cold Drawn	1—4 5—10 11—19 20 & Finer 25—6 6—3 3—1.5 1 & Finer	.012 .008 .005 .003 3 2 12 07	600 185	M2, M7 S4, S2

See section 16 for Cutting Fluid Recommendations

*Feed recommendations apply to CONVENTIONAL (axial-transverse) gear shaving.

†Feeds should be increased 100% for gears shaved by the DIAGONAL (angular-transverse) method

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	FEED*† per rev. of gear in / mm	CUTTER PITCH LINE SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
1. FREE MACHINING CARBON STEELS, WROUGHT (cont.) **Medium Carbon Leaded (cont.)** (materials listed on preceding page)	175 to 225	Hot Rolled, Normalized, Annealed or Cold Drawn	1—4 5—10 11—19 20 & Finer	.012 .008 005 .003	525	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 12 .07	160	S4, S2
	225 to 275	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	1—4 5—10 11—19 20 & Finer	.012 .008 005 .003	425	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 12 .07	130	S4, S2
	275 to 325	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	1—4 5—10 11—19 20 & Finer	012 .008 .005 .003	375	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 12 .07	115	S4, S2
	325 to 375	Quenched and Tempered	1—4 5—10 11—19 20 & Finer	.012 .008 .005 003	300	M3
			25—6 5—3 2—1.5 1 & Finer	.3 .2 12 .07	90	S5
2. CARBON STEELS, WROUGHT **Low Carbon** 1005 1006 1008 1009 1010 1011 1012 1013 1015 1016 1017 1018 1019 1020 1021 1022 1023 1025 1026 1029 1513 1518 1522	85 to 125	Hot Rolled, Normalized, Annealed or Cold Drawn	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	525	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 12 .07	160	S4, S2
	125 to 175	Hot Rolled, Normalized, Annealed or Cold Drawn	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	500	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 12 .07	150	S4, S2
	175 to 225	Hot Rolled, Normalized, Annealed or Cold Drawn	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	450	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 12 .07	135	S4, S2
	225 to 275	Annealed or Cold Drawn	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	375	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 12 .07	110	S4, S2

See section 16 for Cutting Fluid Recommendations
*Feed recommendations apply to CONVENTIONAL (axial-transverse) gear shaving.
†Feeds should be increased 100% for gears shaved by the DIAGONAL (angular-transverse) method

7.4 Gear Shaving

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	FEED*† per rev. of gear in / mm	CUTTER PITCH LINE SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
2. CARBON STEELS, WROUGHT (cont.) **Medium Carbon** 1030 1033 1035 1037 1038 1039 1040 1042 1043 1044 1045 1046 1049 1050 1053 1055 1524 1525 1526 1527 1536 1541 1547 1548 1551 1552	125 to 175	Hot Rolled, Normalized, Annealed or Cold Drawn	1—4 5—10 11—19 20 & Finer	.012 008 005 003	450	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	135	S4, S2
	175 to 225	Hot Rolled, Normalized, Annealed or Cold Drawn	1—4 5—10 11—19 20 & Finer	.012 .008 005 .003	400	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	120	S4, S2
	225 to 275	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	1—4 5—10 11—19 20 & Finer	.012 .008 .005 003	350	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	105	S4, S2
	275 to 325	Hot Rolled, Normalized, Annealed or Quenched and Tempered	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	325	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	100	S4, S2
	325 to 375	Quenched and Tempered	1—4 5—10 11—19 20 & Finer	.012 008 .005 .003	275	M3
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	85	S6
High Carbon 1060 1064 1065 1069 1070 1074 1075 1078 1080 1084 1085 1086 1090 1095 1561 1566 1572	175 to 225	Hot Rolled, Normalized Annealed or Cold Drawn	1—4 5—10 11—19 20 & Finer	.012 008 .005 003	375	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	115	S4, S2
	225 to 275	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	325	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	100	S4, S2
	275 to 325	Hot Rolled, Normalized, Annealed or Quenched and Tempered	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	300	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	90	S4, S2

See section 16 for Cutting Fluid Recommendations.
*Feed recommendations apply to CONVENTIONAL (axial-transverse) gear shaving.
†Feeds should be increased 100% for gears shaved by the DIAGONAL (angular-transverse) method

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH	FEED*† per rev. of gear in	CUTTER PITCH LINE SPEED fpm	HSS TOOL MATERIAL AISI
2. CARBON STEELS, WROUGHT (cont.) **High Carbon (cont.)** (materials listed on preceding page)	325 to 375	Quenched and Tempered	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	250	M3
3. CARBON AND FERRITIC ALLOY STEELS (HIGH TEMPERATURE SERVICE) ASTM A369. Grades FPA, FPB, FP1, FP2, FP12	150 to 200	As Forged	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	450	M2, M7
ASTM A369: Grades FP3b, FP11	150 to 200	Annealed or Normalized and Tempered	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	400	M2, M7
ASTM A369 Grades FP5, FP7, FP9, FP21, FP22	150 to 200	Annealed or Normalized and Tempered	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	350	M2, M7
4. FREE MACHINING ALLOY STEELS, WROUGHT **Medium Carbon Resulfurized** 4140 4145Se 4140Se 4147Te 4142Te 4150	150 to 200	Hot Rolled, Normalized, Annealed or Cold Drawn	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	500	M2, M7
	200 to 250	Hot Rolled, Normalized, Annealed or Cold Drawn	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	450	M2, M7
	275 to 325	Quenched and Tempered	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	325	M2, M7
	325 to 375	Quenched and Tempered	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	250	M3

See section 16 for Cutting Fluid Recommendations

*Feed recommendations apply to CONVENTIONAL (axial-transverse) gear shaving.

†Feeds should be increased 100% for gears shaved by the DIAGONAL (angular-transverse) method.

7.4 Gear Shaving

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	FEED*† per rev. of gear in / mm	CUTTER PITCH LINE SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
4. FREE MACHINING ALLOY STEELS, WROUGHT (cont.) **Medium and High Carbon Leaded** 41L30 41L50 86L20 41L40 43L40 86L40 41L45 51L32 41L47 52L100	150 to 200	Hot Rolled, Normalized, Annealed or Cold Drawn	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	525	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	160	S4, S2
	200 to 250	Hot Rolled, Normalized, Annealed or Cold Drawn	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	450	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	135	S4, S2
	275 to 325	Quenched and Tempered	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	350	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	105	S4, S2
	325 to 375	Quenched and Tempered	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	275	M3
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	84	
5. ALLOY STEELS, WROUGHT **Low Carbon** 4012 4615 4817 8617 4023 4617 4820 8620 4024 4620 5015 8622 4118 4621 5115 8822 4320 4713 5120 9310 4419 4720 6118 94B15 4422 4815 8115 94B17	125 to 175	Hot Rolled, Annealed or Cold Drawn	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	475	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	145	S4, S2
	175 to 225	Hot Rolled, Annealed or Cold Drawn	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	425	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	130	S4, S2
	225 to 275	Hot Rolled, Normalized, Annealed or Cold Drawn	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	350	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	105	S4, S2
	275 to 325	Normalized or Quenched and Tempered	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	300	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	90	S4, S2

See section 16 for Cutting Fluid Recommendations.
*Feed recommendations apply to CONVENTIONAL (axial-transverse) gear shaving.
†Feeds should be increased 100% for gears shaved by the DIAGONAL (angular-transverse) method.

MATERIAL	HARDNESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	FEED*† per rev. of gear in / mm	CUTTER PITCH LINE SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
5. ALLOY STEELS, WROUGHT (cont.) **Low Carbon (cont.)** (materials listed on preceding page)	325 to 375	Normalized or Quenched and Tempered	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	250 76	M3 S5
Medium Carbon 1330 4145 5132 8640 1335 4147 5135 8642 1340 4150 5140 8645 1345 4161 5145 86B45 4027 4340 5147 8650 4028 4427 5150 8655 4032 4626 5155 8660 4037 50B40 5160 8740 4042 50B44 51B60 8742 4047 5046 6150 9254 4130 50B46 81B45 9255 4135 50B50 8625 9260 4137 5060 8627 94B30 4140 50B60 8630 4142 5130 8637	175 to 225	Hot Rolled, Annealed or Cold Drawn	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	400 120	M2, M7 S4, S2
	225 to 275	Annealed, Normalized, Cold Drawn or Quenched and Tempered	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	325 100	M2, M7 S4, S2
	275 to 325	Normalized or Quenched and Tempered	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	275 84	M2, M7 S4, S2
	325 to 375	Normalized or Quenched and Tempered	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	225 69	M3 S5
High Carbon 50100 51100 52100 M-50	175 to 225	Hot Rolled, Annealed or Cold Drawn	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	375 115	M2, M7 S4, S2
	225 to 275	Normalized, Cold Drawn or Quenched and Tempered	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	300 90	M2, M7 S4, S2
	275 to 325	Normalized or Quenched and Tempered	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	250 76	M2, M7 S4, S2

See section 16 for Cutting Fluid Recommendations
*Feed recommendations apply to CONVENTIONAL (axial-transverse) gear shaving
†Feeds should be increased 100% for gears shaved by the DIAGONAL (angular-transverse) method.

7.4 Gear Shaving

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	FEED*† per rev. of gear in / mm	CUTTER PITCH LINE SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
5. ALLOY STEELS, WROUGHT (cont.) **High Carbon (cont.)** (materials listed on preceding page)	325 to 375	Normalized or Quenched and Tempered	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	012 008 .005 .003 .3 .2 .12 .07	200 60	M3 S5
6. HIGH STRENGTH STEELS, WROUGHT 300M 98BV40 4330V D6ac 4340 H11 4340Si H13	225 to 300	Annealed	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	300 90	M2, M7 S4, S2
	300 to 350	Normalized	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	275 84	M3 S5
HP 9-4-20 HP 9-4-25 HP 9-4-30 HP 9-4-45	325 to 375	Annealed	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 003 .3 .2 .12 .07	200 60	M3 S5
7. MARAGING STEELS, WROUGHT 120 Grade 180 Grade	275 to 325	Annealed	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 005 .003 .3 .2 .12 .07	350 105	M2, M7 S4, S2
ASTM A538: Grades A, B, C 200 Grade 250 Grade 300 Grade 350 Grade HY230	275 to 325	Annealed	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	300 90	M2, M7 S4, S2
8. TOOL STEELS, WROUGHT **High Speed** M1 T1 M2 T2 M6 T6 M10	200 to 250	Annealed	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	225 68	M2, M7 S4, S2
High Speed M3-1 M34 M46 M3-2 M36 M47 M4 M41 M4 M7 M42 T5 M30 M43 T8 M33 M44 T15	225 to 275	Annealed	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	200 60	M2, M7 S4, S2

See section 16 for Cutting Fluid Recommendations.
*Feed recommendations apply to CONVENTIONAL (axial-transverse) gear shaving.
†Feeds should be increased 100% for gears shaved by the DIAGONAL (angular-transverse) method.

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	FEED*† per rev. of gear in / mm	CUTTER PITCH LINE SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
Hot Work H10 H22 H11 H23 H12 H24 H13 H25 H14 H26 H19 H42 H21	150 to 200	Annealed	1—4 5—10 11—19 20 & Finer	.012 .008 005 003	325	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	100	S4, S2
	200 to 250	Annealed	1—4 5—10 11—19 20 & Finer	012 .008 005 003	300	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	90	S4, S2
	325 to 375	Quenched and Tempered	1—4 5—10 11—19 20 & Finer	012 .008 .005 .003	250	M3
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	75	S5
Cold Work A2 D3 A3 D4 A4 D5 A6 D7 A7 O1 A8 O2 A9 O6 A10 O7 D2	200 to 250	Annealed	1—4 5—10 11—19 20 & Finer	012 .008 .005 .003	300	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	90	S4, S2
Shock Resisting S1 S2 S5 S6 S7	175 to 225	Annealed	1—4 5—10 11—1^ 20 & Finer	.012 .008 005 003	325	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	100	S4, S2
Mold P2 P4 P5 P6	100 to 150	Annealed	1—4 5—10 11—19 20 & Finer	.012 .008 .005 003	500	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	150	S4, S2
Mold P20 P21	150 to 200	Annealed	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	450	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	125	S4, S2

See section 16 for Cutting Fluid Recommendations.
*Feed recommendations apply to CONVENTIONAL (axial-transverse) gear shaving
†Feeds should be increased 100% for gears shaved by the DIAGONAL (angular-transverse) method.

7.4 Gear Shaving

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	FEED*† per rev. of gear in / mm	CUTTER PITCH LINE SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
8. TOOL STEELS, WROUGHT (cont.)						
Special Purpose			1—4	.012		
			5—10	008	425	M2, M7
			11—19	005		
L2	150		20 & Finer	.003		
L6	to	Annealed	25—6	.3		
L7	200		5—3	.2	130	S4, S2
			2—1.5	.12		
			1 & Finer	.07		
Special Purpose			1—4	.012		
			5—10	.008	375	M2, M7
			11—19	.005		
F1			20 & Finer	.003		
F2	200		25—6	.3		
	to	Annealed	5—3	.2	115	S4, S2
	250		2—1.5	.12		
			1 & Finer	.07		
Water Hardening			1—4	012		
			5—10	008	400	M2, M7
			11—19	.005		
W1, W2, W5			20 & Finer	003		
SAE J438b: Types W108, W109, W110,	150		25—6	.3		
W112, W209, W210, W310	to	Annealed	5—3	.2	120	S4, S2
	200		2—1.5	.12		
			1 & Finer	.07		
9. NITRIDING STEELS, WROUGHT			1—4	012		
			5—10	.008	375	M2, M7
			11—19	.005		
Nitralloy 125			20 & Finer	003		
Nitralloy 135	200		25—6	.3		
Nitralloy 135 Mod.	to	Annealed	5—3	.2	115	S4, S2
Nitralloy 225	250		2—1.5	.12		
Nitralloy 230			1 & Finer	.07		
Nitralloy EZ						
Nitralloy N						
Nitrex 1			1—4	.012		
			5—10	008	275	M3
			11—19	.005		
		Normalized	20 & Finer	003		
	300	or	25—6	.3		
	to	Quenched	5—3	.2	84	S5
	350	and	2—1.5	.12		
		Tempered	1 & Finer	.07		
12. FREE MACHINING STAINLESS STEELS, WROUGHT			1—4	.012		
			5—10	008	300	M2, M7
			11—19	005		
Ferritic			20 & Finer	.003		
	135		25—6	.3		
430F	to	Annealed	5—3	.2	90	S4, S2
430F Se	185		2—1.5	.12		
			1 & Finer	.07		
Austenitic			1—4	.012		
			5—10	.008	250	M2, M7
			11—19	.005		
203EZ			20 & Finer	.003		
303	135		25—6	.3		
303MA	to	Annealed	5—3	.2	76	S4, S2
303Pb	185		2—1.5	.12		
303 Plus X			1 & Finer	.07		
303Se						
			1—4	.012		
			5—10	.008	225	M2, M7
			11—19	005		
		Cold	20 & Finer	.003		
	225		25—6	.3		
	to	Drawn	5—3	.2	[illegible]	S4, S2
	275		2—1.5	.12		
			1 & Finer	.07		

See section 16 for Cutting Fluid Recommendations

*Feed recommendations apply to CONVENTIONAL (axial-transverse) gear shaving

†Feeds should be increased 100% for gears shaved by the DIAGONAL (angular-transverse) method

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	FEED*† per rev. of gear in / mm	CUTTER PITCH LINE SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
Martensitic 416 420F Se 416 Plus X 440F 416Se 440F Se 420F	135 to 185	Annealed	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	300 90	M2, M7 S4, S2
	185 to 240	Annealed or Cold Drawn	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	275 84	M2, M7 S4, S2
	275 to 325	Quenched and Tempered	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	225 69	M2, M7 S4, S2
13. STAINLESS STEELS, WROUGHT **Ferritic** 405 434 409 436 429 442 430 446	135 to 185	Annealed	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	275 84	M2, M7 S4, S2
Austenitic 201 304L 348 202 305 384 301 308 385 302 321 304 347	135 to 185	Annealed	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	225 69	M2, M7 S4, S2
	225 to 275	Cold Drawn	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	200 60	M2, M7 S4, S2
Austenitic 302B 314 309 316 309S 316L 310 317 310S 330	135 to 185	Annealed	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	200 60	M2, M7 S4, S2
	225 to 275	Cold Drawn	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	175 53	M2, M7 S4, S2

See section 16 for Cutting Fluid Recommendations
*Feed recommendations apply to CONVENTIONAL (axial-transverse) gear shaving
†Feeds should be increased 100% for gears shaved by the DIAGONAL (angular-transverse) method

7.4 Gear Shaving

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	FEED*† per rev. of gear in / mm	CUTTER PITCH LINE SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
13. STAINLESS STEELS, WROUGHT (cont.)						
Austenitic						
Nitronic 32 Nitronic 33 Nitronic 40 Nitronic 50 Nitronic 60	210 to 250	Annealed	1—4 5—10 11—19 20 & Finer	.012 008 .005 003	175	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	53	S4, S2
Martensitic						
403 410 420 422 501 502	135 to 175	Annealed	1—4 5—10 11—19 20 & Finer	.012 008 005 003	275	M2, M7
			25—6 5—3 2—1.5 1 & Finer	3 2 12 07	84	S4, S2
	175 to 225	Annealed	1—4 5—10 11—19 20 & Finer	012 008 005 .003	250	M2, M7
			25—6 5—3 2—1.5 1 & Finer	3 2 12 07	76	S4, S2
	275 to 325	Quenched and Tempered	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	200	M2, M7
			25—6 5—3 2—1.5 1 & Finer	3 2 12 07	60	S4, S2
Martensitic						
414 431 Greek Ascoloy	225 to 275	Annealed	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	225	M2, M7
			25—6 5—3 2—1.5 1 & Finer	3 2 12 07	68	S4, S2
	275 to 325	Quenched and Tempered	1—4 5—10 11—19 20 & Finer	012 .008 .005 003	200	M2, M7
			25—6 5—3 2—1.5 1 & Finer	3 2 12 07	60	S4, S2
Martensitic						
440A 440B 440C	225 to 275	Annealed	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	225	M2, M7
			25—6 5—3 2—1.5 1 & Finer	3 2 12 07	68	S4, S2
	275 to 325	Quenched and Tempered	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	200	M2, M7
			25—6 5—3 2—1.5 1 & Finer	3 2 12 07	60	S4, S2

See section 16 for Cutting Fluid Recommendations
*Feed recommendations apply to CONVENTIONAL (axial-transverse) gear shaving
†Feeds should be increased 100% for gears shaved by the DIAGONAL (angular-transverse) method

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	FEED*† per rev. of gear in / mm	CUTTER PITCH LINE SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
14. PRECIPITATION HARDENING STAINLESS STEELS, WROUGHT 15-5 PH 16-6 PH 17-4 PH 17-7 PH 17-14 Cu Mo AF-71 FC-77 Almar 362 (AM-362) AM-350 AM-355 AM-363 Custom 450 Custom 455 HNM PH 13-8 Mo PH 14-8 Mo PH 15-7 Mo Stainless W	150 to 200	Solution Treated	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	225 69	M2, M7 S4, S2
	275 to 325	Solution Treated or Hardened	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	200 60	M2, M7 S4, S2
	325 to 375	Solution Treated or Hardened	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	175 53	M3 S5
15. CARBON STEELS, CAST **Low Carbon** ASTM A426 Grade CP1 1010 1020	100 to 150	Annealed, Normalized or Normalized and Tempered	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	500 150	M2, M7 S4, S2
Medium Carbon ASTM A352 Grades LCA, LCB LCC ASTM A356 Grade 1 1030 1040 1050	125 to 175	Annealed, Normalized or Normalized and Tempered	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	425 130	M2, M7 S4, S2
	175 to 225	Annealed, Normalized or Normalized and Tempered	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	375 115	M2, M7 S4, S2
	250 to 300	Quenched and Tempered	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	325 100	M2, M7 S4, S2

See section 16 for Cutting Fluid Recommendations

*Feed recommendations apply to CONVENTIONAL (axial-transverse) gear shaving.

†Feeds should be increased 100% for gears shaved by the DIAGONAL (angular-transverse) method.

7.4 Gear Shaving

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	FEED*† per rev. of gear in / mm	CUTTER PITCH LINE SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
16. ALLOY STEELS, CAST **Low Carbon** ASTM A217 Grade WC9 ASTM A352 Grades LC3, LC4 ASTM A426 Grades CP2, CP5, CP5b, CP11, CP12, CP15, CP21, CP22 1320 2320 4120 8020 2315 4110 4320 8620	150 to 200	Annealed, Normalized or Normalized and Tempered	1—4 5—10 11—19 20 & Finer	012 008 005 003	425	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	130	S4, S2
	200 to 225	Annealed, Normalized or Normalized and Tempered	1—4 5—10 11—19 20 & Finer	012 008 .005 003	375	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	115	S4, S2
	250 to 300	Quenched and Tempered	1—4 5—10 11—19 20 & Finer	.012 .008 005 .003	325	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	100	S4, S2
Medium Carbon ASTM A27 Grades N1, N2, U-60-30 60-30, 65-35, 70-36 70-40 ASTM A148, Grades 80-40, 80-50, 90-60, 105-85 120-95, 150-125, 175-145 ASTM A216 Grades WCA, WCB, WCC ASTM A217 Grades WC1 WC4 WC5 WC6 ASTM A352, Grades LC1, LC2, LC2-1 ASTM A356 Grades 2, 5, 6, 8, 9, 10 ASTM A389, Grades C23, C24 ASTM A486 Classes 70, 90, 120 ASTM A487, Classes 1N, 2N, 4N, 6N, 8N, 9N, 10N, DN 1Q, 2Q, 4Q, 4QA, 6Q, 7Q, 8Q, 9Q, 10Q 1330 4130 80B30 8640 1340 4140 8040 9525 2325 4330 8430 9530 2330 4340 8440 9535 4125 8030 8630	175 to 225	Annealed, Normalized, or Normalized and Tempered	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	375	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	115	S4, S2
	225 to 250	Normalized, Normalized and Tempered or Quenched and Tempered	1—4 5—10 11—19 20 & Finer	.012 .008 005 .003	325	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	100	S4, S2
	250 to 300	Quenched and Tempered	1—4 5—10 11—19 20 & Finer	012 .008 .005 003	300	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	90	S4, S2
	300 to 350	Quenched and Tempered	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	250	M3
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	76	S5
	350 to 400	Quenched and Tempered	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	200	M3
			25—6 6—3 2—1.5 1 & Finer	.3 .2 .12 .07	60	S5

See section 16 for Cutting Fluid Recommendations

*Feed recommendations apply to CONVENTIONAL (axial-transverse) gear shaving

†Feeds should be increased 100% for gears shaved by the DIAGONAL (angular-transverse) method

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	FEED*† per rev. of gear in / mm	CUTTER PITCH LINE SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
18. STAINLESS STEELS, CAST						
Ferritic						
ASTM A217 Grades C5, C12 ASTM A296 Grades CB-30, CC-50, CE-30, CA6N, CA-6NM, CD4MCu ASTM A297 Grade HC ASTM A487 Class CA6NM ASTM A608 Grade HC30	135 to 185	Annealed	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	012 008 005 003 3 2 12 07	250 76	M2, M7 S4, S2
Austenitic						
ASTM A296 Grades CF-16F, CN-7M CN-7MS ASTM A351 Grade CN-7M	140 to 170	Annealed or Normalized	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	012 .008 .005 .003 3 2 12 07	200 60	M2, M7 S4, S2
Austenitic						
ASTM A296 Grades CF-3 CF-8, CF-8C CF-20 ASTM A351 Grades CF-3 CF-3A, CF-8, CF-8A, CF-8C ASTM A451 Grades CPF3, CPF3A, CPF8, CPF8A, CPF8C, CPF8C (Ta Max) ASTM A452 Grades TP 304H, TP 347H	135 to 185	Annealed or Normalized	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	012 .008 005 003 3 2 12 07	175 53	M2, M7 S4, S2
Austenitic						
ASTM A296 Grades CF-3M, CF-8M, CG-8M, CG-12 CH-20, CK-20 ASTM A351, Grades CF-3M, CF-3MA, CF-8M, CF-10MC, CH-8, CH-10, CH-20, CK-20, HK-30, HK-40, HT-30 ASTM A451: Grades CPF3M, CPF8M, CPF10MC, CPH8, CPH10, CPH20, CPK20 ASTM A452 Grade TP 316H	135 to 185	Annealed or Normalized	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	012 .008 005 .003 3 2 12 07	175 53	M2, M7 S4, S2
Austenitic						
ASTM A297: Grades HD, HE, HF, HH, HI, HK, HL, HN, HP, HT, HU ASTM A608: Grades HD50, HE35, HF30, HH30, HH33, HI35, HK30, HK40, HL30, HL40, HN40, HT50, HU50	160 to 210	As Cast	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 3 2 12 07	175 53	M2, M7 S4, S2

See section 16 for Cutting Fluid Recommendations
*Feed recommendations apply to CONVENTIONAL (axial-transverse) gear shaving
†Feeds should be increased 100% for gears shaved by the DIAGONAL (angular-transverse) method

7.4 Gear Shaving

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	FEED*† per rev. of gear in / mm	CUTTER PITCH LINE SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
18. STAINLESS STEELS, CAST (cont.)						
Martensitic						
ASTM A217 Grade CA-15	135 to 175	Annealed	1—4	.012	250	M2, M7
ASTM A296 Grades CA-15 CA-15M, CA-40			5—10	.008		
ASTM A426 Grades CP7, CP9, CPCA15			11—19	.005		
ASTM A487 Classes CA15a, CA-15M			20 & Finer	.003		
			25—6	.3	.76	S4, S2
			5—3	.2		
			2—1.5	.12		
			1 & Finer	.07		
	175 to 225	Annealed Normalized or Normalized and Tempered	1—4	.012	225	M2, M7
			5—10	.008		
			11—19	.005		
			20 & Finer	.003		
			25—6	.3	.69	S4, S2
			5—3	.2		
			2—1.5	.12		
			1 & Finer	.07		
	275 to 325	Quenched and Tempered	1—4	.012	200	M2, M7
			5—10	.008		
			11—19	.005		
			20 & Finer	.003		
			25—6	.3	.60	S4, S2
			5—3	.2		
			2—1.5	.12		
			1 & Finer	.07		
19. PRECIPITATION HARDENING STAINLESS STEELS, CAST						
ASTM A351 Grade CD-4MCu	325 to 375	Solution Treated	1—4	.012	175	M2, M7
ACI Grade CB-7Cu			5—10	.008		
ACI Grade CD-4MCu			11—19	.005		
17-4 PH			20 & Finer	.003		
AM-355			25—6	.3	.53	S4, S2
			5—3	.2		
			2—1.5	.12		
			1 & Finer	.07		
21. GRAY CAST IRONS						
Ferritic						
ASTM A48 Class 20	120 to 150	Annealed	1—4	.012	325	M2, M7
SAE J431c, Grade G1800			5—10	.008		
			11—19	.005		
			20 & Finer	.003		
			25—6	.3	.100	S4, S2
			5—3	.2		
			2—1.5	.12		
			1 & Finer	.07		
Pearlitic- Ferritic						
ASTM A48 Class 25	160 to 200	As Cast	1—4	.012	300	M2, M7
SAE J431c Grade G2500			5—10	.008		
			11—19	.005		
			20 & Finer	.003		
			25—6	.3	.92	S4, S2
			5—3	.2		
			2—1.5	.12		
			1 & Finer	.07		
Pearlitic						
ASTM A48 Classes 30, 35 40	190 to 220	As Cast	1—4	.012	230	M2 M7
SAE J431c Grade G3000			5—10	.008		
			11—19	.005		
			20 & Finer	.003		
			25—6	.3	.70	S4, S2
			5—3	.2		
			2—1.5	.12		
			1 & Finer	.07		
Pearlitic + Free Carbides						
ASTM A48 Classes 45, 50	220 to 260	As Cast	1—4	.012	200	M2, M7
SAE J431c Grades G3500, G4000			5—10	.008		
			11—19	.005		
			20 & Finer	.003		
			25—6	.3	.60	S4, S2
			5—3	.2		
			2—1.5	.12		
			1 & Finer	.07		

See section 16 for Cutting Fluid Recommendations

*Feed recommendations apply to CONVENTIONAL (axial-transverse) gear shaving.

†Feeds should be increased 100% for gears shaved by the DIAGONAL (angular-transverse) method

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	FEED*† per rev. of gear in / mm	CUTTER PITCH LINE SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
Pearlitic or Acicular + Free Carbides ASTM A48 Classes 55, 60	250 to 320	As Cast or Quenched and Tempered	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	100	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	30	S4, S2
Austenitic (NI-RESIST) ASTM A436, Types 1, 1b, 2, 2b, 3, 4, 5, 6	100 to 250	As Cast	1—4 5—10 11—19 20 & Finer	012 008 005 003	150	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	46	S4, S2
23. DUCTILE CAST IRONS **Ferritic** ASTM A536, Grades 60-40-18, 65-45-12 SAE J434c: Grades D4018, D4512	140 to 190	Annealed	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	400	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	120	S4, S2
Ferritic-Pearlitic ASTM A536: Grade 80-55-06 SAE J434c, Grade D5506	190 to 225	As Cast	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	350	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	100	S4, S2
	225 to 260	As Cast	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	300	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	90	S4, S2
Pearlitic-Martensitic ASTM A536: Grade 100-70-03 SAE J434c: Grade D7003	240 to 300	Normalized and Tempered	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	250	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	76	S4, S2
Martensitic ASTM A536: Grade 120-90-02 SAE J434c: Grade DQ&T	270 to 330	Quenched and Tempered	1—4 5—10 11—19 20 & Finer	012 .008 .005 .003	175	M2, M7
			25—6 6—3 2—1.5 1 & Finer	.3 .2 .12 .07	60	S4, S2
Austenitic (NI-RESIST Ductile) ASTM A439: Types D-2, D-2C, D-3A, D-5 ASTM A571: Type D-2M	120 to 200	Annealed	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	125	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	96	S4, S2

See section 16 for Cutting Fluid Recommendations
*Feed recommendations apply to CONVENTIONAL (axial-transverse) gear shaving.
†Feeds should be increased 100% for gears shaved by the DIAGONAL (angular-transverse) method

7.4 Gear Shaving

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	FEED*† per rev. of gear in / mm	CUTTER PITCH LINE SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
23. DUCTILE CAST IRONS (cont.)			1—4	012		
Austenitic (NI-RESIST Ductile)			5—10	008	100	M2, M7
ASTM A439 Types D-2B, D-3, D-4, D-5B	140 to 275	Annealed	11—19	005		
			20 & Finer	003		
			25—6	.3		
			5—3	.2	30	S4, S2
			2—1.5	.12		
			1 & Finer	.07		
24. MALLEABLE CAST IRONS			1—4	012		
Ferritic			5—10	.008	500	M2, M7
ASTM A47 Grades 32510, 35018			11—19	005		
ASTM A602 Grade M3210	110 to 160	Malleablized	20 & Finer	003		
SAE J158 Grade M3210			25—6	.3		
			5—3	.2	150	S4, S2
			2—1.5	.12		
			1 & Finer	.07		
Pearlitic			1—4	012		
ASTM A220 Grades 40010, 45006, 45008, 50005			5—10	008	400	M2, M7
ASTM A602, Grade M4504, M5003		Malleablized and Heat Treated	11—19	005		
SAE J158 Grades M4504, M5003	160 to 200		20 & Finer	.003		
			25—6	.3		
			5—3	.2	120	S4, S2
			2—1.5	.12		
			1 & Finer	.07		
			1—4	012		
			5—10	008	320	M2, M7
		Malleablized and Heat Treated	11—19	005		
	200 to 240		20 & Finer	.003		
			25—6	.3		
			5—3	.2	100	S4, S2
			2—1.5	.12		
			1 & Finer	.07		
Tempered Martensite			1—4	012		
ASTM A220 Grade 60004			5—10	.008	320	M2, M7
ASTM A602 Grade M5503		Malleablized and Heat Treated	11—19	.005		
SAE J158 Grade M5503	200 to 255		20 & Finer	.003		
			25—6	.3		
			5—3	.2	100	S4, S2
			2—1.5	.12		
			1 & Finer	.07		
Tempered Martensite			1—4	.012		
ASTM A220, Grade 70003			5—10	.008	300	M2, M7
ASTM A602 Grade M7002		Malleablized and Heat Treated	11—19	.005		
SAE J158, Grade M7002	220 to 260		20 & Finer	.003		
			25—6	.3		
			5—3	.2	90	S4, S2
			2—1.5	.12		
			1 & Finer	.07		
Tempered Martensite			1—4	.012		
ASTM A220 Grade 80002			5—10	.008	250	M2, M7
ASTM A602, Grade M8501		Malleablized and Heat Treated	11—19	005		
SAE J158 Grade M8501	240 to 280		20 & Finer	.003		
			25—6	.3		
			5—3	.2	75	S4, S2
			2—1.5	.12		
			1 & Finer	.07		
Tempered Martensite			1—4	.012		
ASTM A220 Grade 90001			5—10	.008	200	M2, M7
ASTM A602 Grade M8501		Malleablized and Heat Treated	11—19	.005		
SAE J158 Grade M8501	250 to 320		20 & Finer	.003		
			25—6	.3		
			5—3	.2	60	S4, S2
			2—1.5	.12		
			1 & Finer	.07		

See section 16 for Cutting Fluid Recommendations

*Feed recommendations apply to CONVENTIONAL (axial-transverse) gear shaving

†Feeds should be increased 100% for gears shaved by the DIAGONAL (angular-transverse) method

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	FEED*† per rev. of gear in / mm	CUTTER PITCH LINE SPEED fpm / m/min	HSS TOOL MATERIAL AISI / ISO
28. ALUMINUM ALLOYS, WROUGHT EC 2218 5252 6253 1060 2219 5254 6262 1100 2618 5454 6463 1145 3003 5456 6951 1175 3004 5457 7001 1235 3005 5652 7004 2011 4032 5657 7005 2014 5005 6053 7039 2017 5050 6061 7049 2018 5052 6063 7050 2021 5056 6066 7075 2024 5083 6070 7079 2025 5086 6101 7175 2117 5154 6151 7178	30 to 80 500kg	Cold Drawn	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	1200 385	M2, M7 S4, S2
	75 to 150 500kg	Solution Treated and Aged	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	1100 335	M2, M7 S4, S2
29. ALUMINUM ALLOYS, CAST **Sand and Permanent Mold** A140 319.0 357.0 A712.0 201.0 328.0 359.0 D712.0 208.0 A332.0 B443.0 713.0 213.0 F332.0 514.0 771.0 222.0 333.0 A514.0 850.0 224.0 354.0 B514.0 A850.0 242.0 355.0 520.0 B850.0 295.0 C355.0 535.0 B295.0 356.0 705.0 308.0 A356.0 707.0 Hiduminium RR-350	40 to 100 500kg	As Cast	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	1100 335	M2, M7 S4, S2
	70 to 125 500kg	Solution Treated and Aged	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	1000 305	M2, M7 S4, S2
34. COPPER ALLOYS, WROUGHT 145 332 360 482 147 335 365 485 173 340 366 544 187 342 367 623 191 349 368 624 314 350 370 638 316 353 377 642 330 356 385 782	10 R_B to 70 R_B	Annealed	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	1000 305	M2, M7 S4, S2
	60 R_B to 100 R_B	Cold Drawn	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	1100 335	M2, M7 S4, S2
190 425 466 667 226 435 467 675 230 442 613 687 240 443 618 691 260 444 630 770 268 445 632 270 464 651 280 465 655	10 R_B to 70 R_B	Annealed	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	600 185	M2, M7 S4, S2
	60 R_B to 100 R_B	Cold Drawn	1—4 5—10 11—19 20 & Finer 25—6 5—3 2—1.5 1 & Finer	.012 .008 .005 .003 .3 .2 .12 .07	700 215	M2, M7 S4, S2

See section 16 for Cutting Fluid Recommendations.
*Feed recommendations apply to CONVENTIONAL (axial-transverse) gear shaving.
†Feeds should be increased 100% for gears shaved by the DIAGONAL (angular-transverse) method.

7.4 Gear Shaving

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	FEED*† per rev. of gear in / mm	CUTTER PITCH LINE SPEED fpm / m/min	HSS TOOL MATERIAL AISI
34. COPPER ALLOYS, WROUGHT (cont.)						
101 125 185 614 102 127 189 619 104 128 192 625 105 129 194 674 107 130 195 688 109 142 210 706 110 143 220 710 111 150 411 715 113 155 413 725 114 162 505 745 115 165 510 752 116 170 511 754 119 172 521 757 120 175 524 121 182 608 122 184 610	10 R_B to 70 R_B	Annealed	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	350	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	105	M2, M7
	60 R_B to 100 R_B	Cold Drawn	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	400	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	125	M2, M7
35. COPPER ALLOYS, CAST						
834 855 934 953 836 857 935 954 838 858 937 956 842 864 938 973 844 867 939 974 848 879 943 976 852 928 944 978 854 932 945	40 to 150 500kg	As Cast	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	900	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	275	M2, M7
817 868 905 947 821 872 915 948 833 874 922 952 853 875 923 955 861 876 925 957 862 876 926 958 865 903 927	40 to 175 500kg	As Cast	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	600	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	175	M2, M7
801 815 828 916 803 818 863 917 805 820 902 962 807 822 907 963 809 824 909 964 811 825 910 966 813 826 911 993 814 827 913	40 to 200 500kg	As Cast	1—4 5—10 11—19 20 & Finer	.012 .008 .005 .003	350	M2, M7
			25—6 5—3 2—1.5 1 & Finer	.3 .2 .12 .07	105	M2, M7

See section 16 for Cutting Fluid Recommendations.
*Feed recommendations apply to CONVENTIONAL (axial-transverse) gear shaving.
†Feeds should be increased 100% for gears shaved by the DIAGONAL (angular-transverse) method.

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	WHEEL IDENTIFI-CATION ANSI / ISO	INFEED in/pass / mm/pass	WHEEL SPEED fpm / m/s	TRAVERSE RATE fpm / m/min
1. FREE MACHINING CARBON STEELS, WROUGHT **Low Carbon Resulfurized** 1108 1115 1118 1212 1109 1116 1119 1213 1110 1117 1211 1215 **Medium Carbon Resulfurized** 1132 1140 1145 1137 1141 1146 1139 1144 1151 **Low Carbon Leaded** 10L18 12L13 12L15 11L17 12L14 **Medium Carbon Leaded** 10L45 11L37 11L44 10L50 11L41	Over 48 R_C	Carburized and/or Quenched and Tempered	1 to 4 5 to 8 10 to 16 16 & finer 25 to 6 5.5 to 3 2.5 to 2 1.5 & finer	A60KV A60KV A80KV A100LV A60KV A60KV A80KV A100LV	.0015 .0012 .0005 .0005 .038 .030 .013 .013	5500 to 6500 28 to 33	20-30 6-9
2. CARBON STEELS, WROUGHT **Low Carbon** 1005 1012 1019 1026 1006 1013 1020 1029 1008 1015 1021 1513 1009 1016 1022 1518 1010 1017 1023 1522 1011 1018 1025 **Medium Carbon** 1030 1042 1053 1541 1033 1043 1055 1547 1035 1044 1524 1548 1037 1045 1525 1551 1038 1046 1526 1552 1039 1049 1527 1040 1050 1536 **High Carbon** 1060 1074 1085 1566 1064 1075 1086 1572 1065 1078 1090 1069 1080 1095 1070 1084 1561	Over 48 R_C	Carburized and/or Quenched and Tempered	1 to 4 5 to 8 10 to 16 16 & finer 25 to 6 5.5 to 3 2.5 to 2 1.5 & finer	A60KV A60KV A80KV A100LV A60KV A60KV A80KV A100LV	.0015 .0012 .0005 .0005 .038 .030 .013 .013	5500 to 6500 28 to 33	20-30 6-9

*See section 16 for Cutting Fluid Recommendations.
See section 20 for additional information

7.5 Gear Grinding, Form

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	WHEEL IDENTIFI-CATION ANSI / ISO	INFEED in/pass / mm/pass	WHEEL SPEED fpm / m/s	TRAVERSE RATE fpm / m/min
4. FREE MACHINING ALLOY STEELS, WROUGHT **Medium Carbon Resulfurized** 4140 4142Te 4147Te 4140Se 4145Se 4150 **Medium and High Carbon Leaded** 41L30 41L47 51L32 86L40 41L40 41L50 52L100 41L45 43L40 86L20	Over 48 R_C	Carburized and/or Quenched and Tempered	1 to 4 5 to 8 10 to 16 16 & finer	A60KV A60KV A80KV A100LV	.0015 .0012 .0005 0005	5500 to 6500	20-30
			25 to 6 6.5 to 3 2.5 to 2 1.5 & finer	A60KV A60KV A80KV A100LV	.038 .030 .013 .013	28 to 33	6-9
5. ALLOY STEELS, WROUGHT **Low Carbon** 4012 4615 4817 8617 4023 4617 4820 8620 4024 4620 5015 8622 4118 4621 5115 8822 4320 4718 5120 9310 4419 4720 6118 94B15 4422 4815 8115 94B17 **Medium Carbon** 1330 4145 5132 8640 1335 4147 5135 8642 1340 4150 5140 8645 1345 4161 5145 86B45 4027 4340 5147 8650 4028 4427 5150 8655 4032 4626 5155 8660 4037 50B40 5160 8740 4042 50B44 51B60 8742 4047 5046 6150 9254 4130 50B46 81B45 9255 4135 50B50 8625 9260 4137 5060 8627 94B30 4140 50B60 8630 4142 5130 8637 **High Carbon** 50100 51100 52100 M-50	Over 48 R_C	Carburized and/or Quenched and Tempered	1 to 4 5 to 8 10 to 16 16 & finer	A60KV A60KV A80KV A100LV	.0015 .0012 .0005 .0005	5500 to 6500	20-30
			25 to 6 6.5 to 3 2.5 to 2 1.5 & finer	A60KV A60KV A80KV A100LV	.038 .030 .013 .013	28 to 33	6-9

*See section 16 for Cutting Fluid Recommendations.
See section 20 for additional information.

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	WHEEL IDENTIFI-CATION ANSI / ISO	INFEED in/pass / mm/pass	WHEEL SPEED fpm / m/s	TRAVERSE RATE fpm / m/min
6. HIGH STRENGTH STEELS, WROUGHT 300M 4330V 4340 4340Si 98BV40 D6ac H11 H13 HP 9-4-20 HP 9-4-25 HP 9-4-30 HP 9-4-45	Over 48 R_C	Quenched and Tempered	1 to 4 5 to 8 10 to 16 16 & finer	A60KV A60KV A80KV A100LV	.0015 .0012 .0005 .0005	5500 to 6500	20-30
			25 to 6 5.5 to 3 2.5 to 2 1.5 & finer	A60KV A60KV A80KV A100LV	.038 .030 .013 .013	28 to 33	6-9
7. MARAGING STEELS, WROUGHT ASTM A538: Grades A, B, C 120 Grade 180 Grade 200 Grade 250 Grade 300 Grade 350 Grade HY230	Over 48 R_C	Maraged	1 to 4 5 to 8 10 to 16 16 & finer	A60KV A60KV A80KV A100LV	.0015 .0012 .0005 .0005	5500 to 6500	20-30
			25 to 6 5.5 to 3 2.5 to 2 1.5 & finer	A80KV A60KV A80KV A100LV	.038 .030 .013 .013	28 to 33	6-9
8. TOOL STEELS, WROUGHT **Group I** A2 H13 L6 P20 A3 H14 L7 P21 A4 H19 O1 S1 A6 H21 O2 S2 A8 H22 O6 S5 A9 H23 O7 S6 A10 H24 P2 S7 H10 H25 P4 W1 H11 H26 P5 W2 H12 L2 P6 W5 SAE J438b, Types W108, W109, W110, W112, W209, W210, W310	Over 48 R_C	Quenched and Tempered	1 to 4 5 to 8 10 to 16 16 & finer	A80JV A80KV A100KV A120KV	.0015 .0012 .0005 .0005	5500 to 6500	20-30
			25 to 6 5.5 to 3 2.5 to 2 1.5 & finer	A80JV A80KV A100KV A120KV	.038 .030 .013 .013	28 to 33	6-9
Group II D2 F2 M10 T4 D3 H42 M30 T8 D4 M1 M42 D5 M2 T1 F1 M3-1 T2	Over 48 R_C	Quenched and Tempered	1 to 4 5 to 8 10 to 16 16 & finer	A80JV A80KV A100KV A120KV	.0015 .0012 .0005 .0005	5500 to 6500	20-30
			25 to 6 5.5 to 3 2.5 to 2 1.5 & finer	A80JV A80KV A100KV A120KV	.038 .030 .013 .013	28 to 33	6-9

*See section 16 for Cutting Fluid Recommendations.
See section 20 for additional information.

7.5 Gear Grinding, Form

MATERIAL	HARD-NESS Bhn	CONDITION	DIAMETRAL PITCH / MODULE	WHEEL IDENTIFI-CATION ANSI / ISO	INFEED in/pass / mm/pass	WHEEL SPEED fpm / m/s	TRAVERSE RATE fpm / m/min
8. TOOL STEELS, WROUGHT (cont.) **Group III** A7 M7 M41 M47 D7 M33 M43 T5 M3-2 M34 M44 T6 M6 M36 M46	Over 48 R_C	Quenched and Tempered	1 to 4 5 to 8 10 to 16 16 & finer	A80JV A80KV A100KV A120KV	.0015 .0012 .0005 0005	5500 to 6500	20-30
			25 to 6 5.5 to 3 2.5 to 2 1.5 & finer	A80JV A80KV A100KV A120KV	.038 .030 .013 .013	28 to 33	6-9
Group IV M4 T15	Over 48 R_C	Quenched and Tempered	1 to 4 5 to 8 10 to 16 16 & finer	A80JV A80KV A100KV A120KV	.0015 .0012 .0005 0005	5500 to 6500	20-30
			25 to 6 5.5 to 3 2.5 to 2 1.5 & finer	A80JV A80KV A100KV A120KV	.038 .030 .013 .013	28 to 33	6-9
17. TOOL STEELS, CAST ASTM A597 Grades CA-2, CD-2, CD-5, CH-12, CH-13, CO-1, CS-5	Over 48 R_C	Quenched and Tempered	1 to 4 5 to 8 10 to 16 16 & finer	A80JV A80KV A100KV A120KV	.0015 .0012 .0005 .0005	5500 to 6500	20-30
			25 to 6 5.5 to 3 2.5 to 2 1.5 & finer	A80JV A80KV A100KV A120KV	.038 .030 .013 .013	28 to 33	6-9

*See section 16 for Cutting Fluid Recommendations.
See section 20 for additional information.

SECTION 8

GRINDING OPERATIONS

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Surface Grinding-Horizontal Spindle, Reciprocating Table 8.1

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE SPEED fpm m/min	DOWNFEED in/pass mm/pass	CROSSFEED in/pass mm/pass	WHEEL* IDENTIFI-CATION ANSI ISO
1. FREE MACHINING CARBON STEELS, WROUGHT **Low Carbon Resulfurized** *1108 1115 1118 1212 1109 1116 1119 1213 1110 1117 1211 1215 **Medium Carbon Resulfurized** 1132 1140 1145 1137 1141 1146 1139 1144 1151 **Low Carbon Leaded** 10L18 12L13 12L15 11L17 12L14 **Medium Carbon Leaded** 10L45 11L37 11L44 10L50 11L41	50 R_C max	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .003 Finish 001 max. Rough: .075 Finish .025 max.	.050-.500 (Max: 1/4 of Wheel Width) 1.25-12.5 (Max: 1/4 of Wheel Width)	A46JV A46JV
	Over 50 R_C	Carburized and/or Quenched and Tempered	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough .002 Finish 0005 max Rough: .050 Finish .013 max.	.025-.250 (Max: 1/10 of Wheel Width) .65-6.5 (Max: 1/10 of Wheel Width)	A46IV A46IV
2. CARBON STEELS, WROUGHT **Low Carbon** 1005 1012 1019 1026 1006 1013 1020 1029 1008 1015 1021 1513 1009 1016 1022 1518 1010 1017 1023 1522 1011 1018 1025 **Medium Carbon** 1030 1042 1053 1541 1033 1043 1055 1547 1035 1044 1524 1548 1037 1045 1525 1551 1038 1046 1526 1552 1039 1049 1527 1040 1050 1536 **High Carbon** 1060 1074 1085 1566 1064 1075 1086 1572 1065 1078 1090 1069 1080 1095 1070 1084 1561	50 R_C max.	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .003 Finish 001 max. Rough: .075 Finish .025 max.	.050-.500 (Max: 1/4 of Wheel Width) 1.25-12.5 (Max: 1/4 of Wheel Width)	A46JV A46JV
	Over 50 R_C	Carburized and/or Quenched and Tempered	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough. .002 Finish .0005 max. Rough: .050 Finish .013 max.	.025-.250 (Max: 1/10 of Wheel Width) .65-6.5 (Max: 1/10 of Wheel Width)	A46IV A46IV
3. CARBON AND FERRITIC ALLOY STEELS (HIGH TEMPERATURE SERVICE) ASTM A369: Grades FPA, FPB, FP1, FP2, FP3b, FP5, FP7, FP9, FP11, FP12, FP21, FP22	150 to 200	As Forged, Annealed or Normalized and Tempered	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .003 Finish .001 max. Rough: .075 Finish .025 max.	.050-.500 (Max: 1/4 of Wheel Width) 1.25-12.5 (Max: 1/4 of Wheel Width)	A46JV A46JV

See section 16 for Cutting Fluid Recommendations.
*Wheel recommendations are for wet grinding. For DRY grinding—use a softer grade wheel. Also see section 20.2, Grinding Guidelines

8.1 Surface Grinding-Horizontal Spindle, Reciprocating Table

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm / m/s	TABLE SPEED fpm / m/min	DOWNFEED in/pass / mm/pass	CROSSFEED in/pass / mm/pass	WHEEL* IDENTIFI-CATION ANSI / ISO
4. FREE MACHINING ALLOY STEELS, WROUGHT **Medium Carbon Resulfurized** 4140 4142Te 4147Te 4140Se 4145Se 4150 **Medium and High Carbon Leaded** 41L30 41L47 51L32 86L40 41L40 41L50 52L100 41L45 43L40 86L20	50 R_C max.	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	5500 to 6500	50 to 100	Rough: .003 Finish .001 max.	.050-.500 (Max: 1/4 of Wheel Width)	A46JV
			28 to 33	15 to 30	Rough: .075 Finish .025 max.	1.25-12.5 (Max: 1/4 of Wheel Width)	A46JV
	Over 50 R_C	Carburized and/or Quenched and Tempered	5500 to 6500	50 to 100	Rough: .002 Finish .0005 max.	.025-.250 (Max: 1/10 of Wheel Width)	A46IV
			28 to 33	15 to 30	Rough: .050 Finish .013 max.	.65-6.5 (Max: 1/10 of Wheel Width)	A46IV
5. ALLOY STEELS, WROUGHT **Low Carbon** 4012 4615 4817 8617 4023 4617 4820 8620 4024 4620 5015 8622 4118 4621 5115 8822 4320 4718 5120 9310 4419 4720 6118 94B15 4422 4815 8115 94B17 **Medium Carbon** 1330 4145 5132 8640 1335 4147 5135 8642 1340 4150 5140 8645 1345 4161 5145 86B45 4027 4340 5147 8650 4028 4427 5150 8655 4032 4626 5155 8660 4037 50B40 5160 8740 4042 50B44 51B60 8742 4047 5046 6150 9254 4130 50B46 81B45 9255 4135 50B50 8625 9260 4137 5060 8627 94B30 4140 50B60 8630 4142 5130 8637 **High Carbon** 50100 51100 52100 M-50	50 R_C max.	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	5500 to 6500	50 to 100	Rough: .003 Finish .0005 max.	.050-.500 (Max: 1/4 of Wheel Width)	A46JV
			28 to 33	15 to 30	Rough: .075 Finish .013 max.	1.25-12.5 (Max: 1/4 of Wheel Width)	A46JV
	Over 50 R_C	Carburized and/or Quenched and Tempered	3000 to 4000	50 to 100	Rough: .002 Finish .0005 max.	.025-.250 (Max: 1/10 of Wheel Width)	A46IV
			15 to 28	15 to 30	Rough: .050 Finish .013 max.	.65-6.5 (Max: 1/10 of Wheel Width)	A46IV
6. HIGH STRENGTH STEELS, WROUGHT 300M 4330V 4340 4340Si 98BV40 D6ac H11 H13 HP 9-4-20 HP 9-4-25 HP 9-4-30 HP 9-4-45	50 R_C max.	Annealed, Normalized or Quenched and Tempered	4000 to 6000	50 to 100	Rough: .002 Finish .0005 max.	.050-.250 (Max: 1/4 of Wheel Width)	A46JV
	Over 50 R_C	Quenched and Tempered	3000 to 4000	50 to 100	Rough: .002 Finish .0005 max.	.025-.250 (Max: 1/10 of Wheel Width)	A60HV

See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding. For DRY grinding—use a softer grade wheel. Also see section 20.2, Grinding Guidelines.

Surface Grinding-Horizontal Spindle, Reciprocating Table 8.1

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm / m/s	TABLE SPEED fpm / m/min	DOWNFEED in/pass / mm/pass	CROSSFEED in/pass / mm/pass	WHEEL* IDENTIFI-CATION ANSI / ISO
7. MARAGING STEELS, WROUGHT ASTM A538 Grades A, B, C 120 Grade 180 Grade 200 Grade 250 Grade 300 Grade 350 Grade HY230	50 R_C max.	Annealed or Maraged	4000 to 6000 20 to 30	50 to 100 15 to 30	Rough: .003 Finish .001 max Rough: .075 Finish .025 max.	050-.500 (Max: 1/4 of Wheel Width) 1.25-12.5 (Max: 1/4 of Wheel Width)	A46JV A46JV
	Over 50 R_C	Maraged	3000 to 4000 15 to 20	50 to 100 15 to 30	Rough: .002 Finish .0005 max. Rough: .050 Finish .013 max.	025-.250 (Max: 1/10 of Wheel Width) .65-6.5 (Max: 1/10 of Wheel Width)	A60HV A60HV
8. TOOL STEELS, WROUGHT **Group I** A2 H13 L6 P20 A3 H14 L7 P21 A4 H19 O1 S1 A6 H21 O2 S2 A8 H22 O6 S5 A9 H23 O7 S6 A10 H24 P2 S7 H10 H25 P4 W1 H11 H26 P5 W2 H12 L2 P6 W5 SAE J438b: Types W108, W109, W110, W112, W209, W210, W310	50 R_C max.	Annealed or Quenched and Tempered	5500 to 6500 25 to 35	50 to 100 15 to 30	Rough: .003 Finish .0005 max. Rough: .075 Finish .013 max.	.050-.500 (Max: 1/5 of Wheel Width) 1.25-12.5 (Max: 1/5 of Wheel Width)	A46JV A46JV
	Over 50 R_C	Quenched and Tempered	3000 to 4000 15 to 20	50 to 100 15 to 30	Rough: .002 Finish .0005 max. Rough: .050 Finish .013 max.	.025-.250 (Max. 1/10 of Wheel Width) .65-6.5 (Max: 1/10 of Wheel Width)	A46IV A46IV
Group II D2 F2 M10 T4 D3 H42 M30 T8 D4 M1 M42 D5 M2 T1 F1 M3-1 T2	50 R_C max.	Annealed or Quenched and Tempered	5500 to 6500 25 to 35	50 to 100 15 to 30	Rough: .003 Finish .0005 max. Rough: .075 Finish .013 max.	.050-.500 (Max: 1/5 of Wheel Width) 1.25-12.5 (Max: 1/5 of Wheel Width)	A46JV A46JV
	50 R_C to 58 R_C	Quenched and Tempered	3000 to 4000 15 to 20	50 to 100 15 to 30	Rough: .002 Finish .0005 max. Rough: .050 Finish .013 max.	.025-.250 (Max. 1/10 of Wheel Width) .65-6.5 (Max: 1/10 of Wheel Width)	A46IV A46IV
	Over 58 R_C	Quenched and Tempered	3000 to 4000 15 to 20	50 to 100 15 to 30	Rough: .001 Finish .0005 max. Rough: .025 Finish .013 max.	.025-.250 (Max: 1/10 of Wheel Width) .65-6.5 (Max: 1/10 of Wheel Width)	A60HV A60HV
Group III A7 M7 M41 M47 D7 M33 M43 T5 M3-2 M34 M44 T6 M6 M36 M46	50 R_C max.	Annealed or Quenched and Tempered	4000 to 6000 20 to 30	50 to 100 15 to 30	Rough: .002 Finish .0005 max. Rough: .050 Finish .013 max.	.025-.250 (Max: 1/8 of Wheel Width) .65-6.5 (Max: 1/10 of Wheel Width)	A46IV A46IV
	50 R_C to 58 R_C	Quenched and Tempered	3000 to 4000 15 to 20	75 to 150 30 to 60	Rough: .002 Finish .0005 max. Rough: .050 Finish .013 max.	.025-.250 (Max: 1/10 of Wheel Width) .65-6.5 (Max: 1/10 of Wheel Width)	A60IV A60IV

See section 16 for Cutting Fluid Recommendations.
*Wheel recommendations are for wet grinding. For DRY grinding—use a softer grade wheel. Also see section 20.2, Grinding Guidelines.

8.1 Surface Grinding-Horizontal Spindle, Reciprocating Table

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm / m/s	TABLE SPEED fpm / m/min	DOWNFEED in/pass / mm/pass	CROSSFEED in/pass / mm/pass	WHEEL* IDENTIFI-CATION ANSI / ISO
8. TOOL STEELS, WROUGHT (cont.) **Group III (cont.)** (materials listed on preceding page)	Over 58 R_C	Quenched and Tempered	3000 to 4000 15 to 20	75 to 150 23 to 46	Rough .001 Finish 0003 max. Rough: .025 Finish .008 max.	.020- 200 (Max: 1/12 of Wheel Width) .50-5.0 (Max: 1/12 of Wheel Width)	A60HV A60HV
Group IV M4 T15	50 R_C max.	Annealed or Quenched and Tempered	4000 to 6000 20 to 30	50 to 100 15 to 30	Rough: 002 Finish .0005 max. Rough: .050 Finish .013 max.	020- 200 (Max: 1/10 of Wheel Width) .50-5.0 (Max: 1/10 of Wheel Width)	A46HV A46HV
	50 R_C to 58 R_C	Quenched and Tempered	3000 to 4000 15 to 20	75 to 150 23 to 46	Rough: .001 Finish .0003 max. Rough: .025 Finish .008 max.	.020-.200 (Max: 1/12 of Wheel Width) .50-5.0 (Max: 1/12 of Wheel Width)	A60HV A60HV
	Over 58 R_C	Quenched and Tempered	3000 to 4000 15 to 20	75 to 150 23 to 46	Rough .001 Finish 0003 max. Rough: .025 Finish .008 max.	.020-.200 (Max: 1/12 of Wheel Width) .50-5.0 (Max: 1/12 of Wheel Width)	A60GV A60GV
9. NITRIDING STEELS, WROUGHT Nitralloy 125 Nitralloy 135 Nitralloy 135 Mod. Nitralloy 225 Nitralloy 230 Nitralloy EZ Nitralloy N Nitrex 1	200 to 350	Annealed, Normalized or Quenched and Tempered	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .003 Finish .001 max. Rough: .075 Finish .025 max.	.050-.500 (Max: 1/4 of Wheel Width) 1.25-12.5 (Max: 1/4 of Wheel Width)	A46JV A46JV
	60 R_C to 65 R_C	Nitrided	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .001 Finish .0003 max. Rough: .025 Finish .008 max.	.025-.250 (Max: 1/10 of Wheel Width) .65-6.5 (Max: 1/10 of Wheel Width)	A60HV A60HV
10. ARMOR PLATE, SHIP PLATE, AIRCRAFT PLATE, WROUGHT HY80 MIL-S-12560 HY100 MIL-S-16216 HY180	45 R_C max.	Annealed or Quenched and Tempered	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .003 Finish .001 max. Rough: .075 Finish .025 max.	.050-.500 (Max: 1/4 of Wheel Width) 1.25-12.5 (Max: 1/4 of Wheel Width)	A46KV A46KV
12. FREE MACHINING STAINLESS STEELS, WROUGHT **Ferritic** 430F 430F Se	135 to 185	Annealed	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .002 Finish .0005 max. Rough: .050 Finish .013 max.	.050-.500 (Max: 1/4 of Wheel Width) 1.25-12.5 (Max: 1/4 of Wheel Width)	A46IV A46IV
Austenitic 203EZ 303Pb 303 303 Plus X 303MA 303Se	135 to 275	Annealed or Cold Drawn	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .002 Finish .0005 max. Rough: .050 Finish .013 max.	.050-.500 (Max: 1/4 of Wheel Width) 1.25-12.5 (Max: 1/4 of Wheel Width)	C46JV C46JV

See section 16 for Cutting Fluid Recommendations
*Wheel recommendations are for wet grinding. For DRY grinding—use a softer grade wheel. Also see section 20.2, Grinding Guidelines.

Surface Grinding-Horizontal Spindle, Reciprocating Table 8.1

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE SPEED fpm m/min	DOWNFEED in/pass mm/pass	CROSSFEED in/pass mm/pass	WHEEL* IDENTIFI-CATION ANSI ISO
Martensitic 416 420F Se 416 Plus X 440 F 416Se 440F Se 420F	135 to 240	Annealed or Cold Drawn	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .002 Finish .0005 max. Rough: .050 Finish .013 max.	.050-.500 (Max: 1/4 of Wheel Width) 1.25-12.5 (Max: 1/4 of Wheel Width)	A46IV A46IV
	Over 275	Quenched and Tempered	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .001 Finish .0005 max. Rough: .025 Finish .013 max.	.025-.250 (Max: 1/10 of Wheel Width) .65-6.5 (Max: 1/10 of Wheel Width)	A46HV A46HV
13. STAINLESS STEELS, WROUGHT **Ferritic** 405 429 434 442 409 430 436 446	135 to 185	Annealed	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .002 Finish .0005 max. Rough: .050 Finish .013 max.	.050-.500 (Max: 1/4 of Wheel Width) 1.25-12.5 (Max: 1/4 of Wheel Width)	A46IV A46IV
Austenitic 201 304L 310S 330 202 305 314 347 301 308 316 348 302 309 316L 384 302B 309S 317 385 304 310 321	135 to 275	Annealed or Cold Drawn	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .002 Finish .0005 max. Rough: .050 Finish .013 max.	.050-.500 (Max: 1/4 of Wheel Width) 1.25-12.5 (Max: 1/4 of Wheel Width)	C46JV C46JV
Austenitic Nitronic 32 Nitronic 33 Nitronic 40 Nitronic 50 Nitronic 60	210 to 250	Annealed	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .002 Finish .0005 max. Rough: .050 Finish .013 max.	.050-.500 (Max: 1/4 of Wheel Width) 1.25-12.5 (Max: 1/4 of Wheel Width)	C46JV C46JV
	325 to 375	Cold Drawn	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .001 Finish .0005 max. Rough: .025 Finish .013 max.	.025-.250 (Max: 1/10 of Wheel Width) .65-6.5 (Max: 1/10 of Wheel Width)	C46HV C46HV
Martensitic 403 422 440C 410 431 501 414 440A 502 420 440B Greek Ascoloy	135 to 275	Annealed	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .002 Finish .0005 max. Rough: .050 Finish .013 max.	.050-.500 (Max: 1/4 of Wheel Width) 1.25-12.5 (Max: 1/4 of Wheel Width)	A46IV A46IV
	Over 275	Quenched and Tempered	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .001 Finish .0003 max. Rough: .025 Finish .013 max.	.025-.250 (Max: 1/10 of Wheel Width) .65-6.5 (Max: 1/10 of Wheel Width)	A46HV A46HV

See section 16 for Cutting Fluid Recommendations
*Wheel recommendations are for wet grinding. For DRY grinding—use a softer grade wheel. Also see section 20.2, Grinding Guidelines.

8.1 Surface Grinding-Horizontal Spindle, Reciprocating Table

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm / m/s	TABLE SPEED fpm / m/min	DOWNFEED in. pass / mm/pass	CROSSFEED in/pass / mm/pass	WHEEL* IDENTIFI-CATION ANSI / ISO
14. PRECIPITATION HARDENING STAINLESS STEELS, WROUGHT 15-5 PH 16-6 PH 17-4 PH 17-7 PH 17-14 Cu Mo AF-71 AFC-77 Almar 362 (AM-362) AM-350 AM-355 AM-363 Custom 450 Custom 455 HNM PH 13-8 Mo PH 14-8 Mo PH 15-7 Mo Stainless W	150 to 200	Solution Treated	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .002 Finish .0005 max. Rough: .050 Finish .013 max.	.050-.500 (Max: 1/4 of Wheel Width) 1.25-12.5 (Max: 1/4 of Wheel Width)	A46IV A46IV
	275 to 440	Solution Treated or Hardened	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .001 Finish .0005 max. Rough: .025 Finish .013 max.	.025-.250 (Max: 1/10 of Wheel Width) .65-6.5 (Max: 1/10 of Wheel Width)	A46HV A46HV
15. CARBON STEELS, CAST **Low Carbon** ASTM A426, Grade CP1 1010 1020 **Medium Carbon** ASTM A352: Grades LCA, LCB, LCC ASTM A356: Grade 1 1030 1040 1050	100 to 300	Annealed, Normalized, Normalized and Tempered, or Quenched and Tempered	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .003 Finish .001 max. Rough: .075 Finish .025 max.	.050-.500 (Max: 1/4 of Wheel Width) 1.25-12.5 (Max: 1/4 of Wheel Width)	A46JV A46JV
	Over 50 R_C	Carburized and/or Quenched and Tempered	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .002 Finish .0005 max. Rough: .050 Finish .013 max.	.025-.250 (Max: 1/10 of Wheel Width) .65-6.5 (Max: 1/10 of Wheel Width)	A46IV A46IV
16. ALLOY STEELS, CAST **Low Carbon** ASTM A217: Grade WC9 ASTM A352: Grades LC3, LC4 ASTM A426: Grades CP2, CP5, CP5b, CP11, CP12, CP15, CP21, CP22 1320 2320 4120 8020 2315 4110 4320 8620 **Medium Carbon** ASTM A27: Grades N1, N2, U-60-30, 60-30, 65-35, 70-36, 70 40 ASTM A148: Grades 80-40, 80-50, 90-60, 105-85, 120-95, 150-125, 175-145 ASTM A216: Grades WCA, WCB, WCC ASTM A217: Grades WC1, WC4, WC5, WC6 ASTM A352: Grades LC1, LC2, LC2-1 (materials continued on next page)	150 to 400	Annealed, Normalized, Normalized and Tempered, or Quenched and Tempered	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .003 Finish .0005 max. Rough: .075 Finish .013 max.	.050-.500 (Max: 1/4 of Wheel Width) 1.25-12.5 (Max: 1/4 of Wheel Width)	A46JV A46JV
	Over 50 R_C	Carburized and/or Quenched and Tempered	3000 to 4000 28 to 33	50 to 100 15 to 30	Rough: .002 Finish .0005 max. Rough: .050 Finish .013 max.	.025-.250 (Max: 1/10 of Wheel Width) .65-6.5 (Max: 1/10 of Wheel Width)	A46IV A46IV

See section 16 for Cutting Fluid Recommendations.
*Wheel recommendations are for wet grinding. For DRY grinding—use a softer grade wheel. Also see section 20.2, Grinding Guidelines.

Surface Grinding-Horizontal Spindle, Reciprocating Table 8.1

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE SPEED fpm m/min	DOWNFEED in/pass mm/pass	CROSSFEED in/pass mm/pass	WHEEL* IDENTIFI-CATION ANSI ISO
16. ALLOY STEELS, CAST (cont.) **Medium Carbon (cont.)** (materials continued from preceding page) ASTM A356 Grades 2, 5, 6, 8, 9, 10 ASTM A389: Grades C23, C24 ASTM A486. Classes 70, 90, 120 ASTM A487 Classes 1N, 2N, 4N, 6N, 8N, 9N, 10N, DN, 1Q, 2Q, 4Q, 4QA, 6Q, 7Q, 8Q, 9Q, 10Q 1330 4130 80B30 8640 1340 4140 8040 9525 2325 4330 8430 9530 2330 4340 8440 9535 4125 8030 8630							
17. TOOL STEELS, CAST **Group I** ASTM A597· Grades CA-2, CH-12, CH-13, CO-1, CS-5	50 R_C max.	Annealed or Quenched and Tempered	5500 to 6500	50 to 100	Rough: .003 Finish .0005 max.	.050-.500 (Max: 1/5 of Wheel Width)	A46JV
	50 R_C to 58 R_C	Quenched and Tempered	3000 to 4000	50 to 100	Rough. .002 Finish 0005 max.	.025-.250 (Max: 1/10 of Wheel Width)	A46IV
	Over 58 R_C	Quenched and Tempered	3000 to 4000	50 to 100	Rough: .001 Finish .0005 max.	.025-.250 (Max: 1/10 of Wheel Width)	A60IV
Group II ASTM A597: Grades CD-2, CD-5	200 to 250	Annealed	5500 to 6500	50 to 100	Rough: .003 Finish .0005 max.	.050-.500 (Max: 1/5 of Wheel Width)	A46JV
	48 R_C to 56 R_C	Quenched and Tempered	3000 to 4000	50 to 100	Rough: .002 Finish .0005 max.	.025-.250 (Max: 1/10 of Wheel Width)	A46IV
	Over 56 R_C	Quenched and Tempered	3000 to 4000	50 to 100	Rough: .001 Finish .0005 max.	.025-.250 (Max: 1/10 of Wheel Width)	A60HV

See section 16 for Cutting Fluid Recommendations.
*Wheel recommendations are for wet grinding. For DRY grinding—use a softer grade wheel Also see section 20 2, Grinding Guidelines.

Surface Grinding-Horizontal Spindle, Reciprocating Table

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE SPEED fpm m/min	DOWNFEED in/pass mm/pass	CROSSFEED in/pass mm/pass	WHEEL* IDENTIFI-CATION ANSI ISO
18. STAINLESS STEELS, CAST			5500 to 6500	50 to 100	Rough: .002 Finish .0005 max	.050- 500 (Max. 1/4 of Wheel Width)	A46IV
Ferritic	135 to 185	Annealed	28 to 33	15 to 30	Rough: .050 Finish .013 max	1.25-12.5 (Max. 1/4 of Wheel Width)	A46IV
ASTM A217: Grades C5, C12							
ASTM A296: Grades CB-30, CC-50, CE-30, CA6N, CA-6NM, CD4MCu							
ASTM A297: Grade HC							
ASTM A487: Class CA6NM							
ASTM A608: Grade HC30							
Austenitic			5500 to 6500	50 to 100	Rough .002 Finish .0005 max	.050-.500 (Max. 1/4 of Wheel Width)	C46JV
ASTM A296: Grades CF-3, CF-3M, CF-8, CF-8C, CF-8M, CF-16F, CF-20, CG-8M, CG-12, CH-20, CK-20, CN-7M, CN-7MS	135 to 210	Annealed, Normalized or As Cast	28 to 33	15 to 30	Rough: .050 Finish .013 max	1.25-12.5 (Max. 1/4 of Wheel Width)	C46JV
ASTM A297: Grades HD, HE, HF, HH, HI, HK, HL, HN, HP, HT, HU							
ASTM A351: Grades CF-3, CF-3A, CF-3M, CF-3MA, CF-8, CF-8A, CF-8C, CF-8M, CF-10MC, CH-8, CH-10, CH-20, CK-20, CN-7M, HK-30, HK-40, HT-30							
ASTM A451: Grades CPF8A, CPF3, CPF3A, CPF3M, CPF8, CPF8C, CPF8C (Ta Max.), CPF8M, CPF10MC, CPH8, CPH10, CPH20, CPK20							
ASTM A452: Grades TP 304H, TP 316H, TP 347H							
ASTM A608: Grades HD50, HE35, HF30, HH30, HH33, HI35, HK30, HK40, HL30, HL40, HN40, HT50, HU50							
Martensitic			5500 to 6500	50 to 100	Rough: .002 Finish .0005 max.	.050-.500 (Max: 1/4 of Wheel Width)	A46IV
ASTM A217: Grade CA-15	135 to 225	Annealed, Normalized or Normalized and Tempered	28 to 33	15 to 30	Rough: .050 Finish .013 max	1.25-12.5 (Max. 1/4 of Wheel Width)	A46IV
ASTM A296: Grades CA-15, CA-15M, CA-40							
ASTM A426: Grades CP7, CP9, CPCA15							
ASTM A487: Classes CA15a, CA-15M			5500 to 6500	50 to 100	Rough: .001 Finish .0005 max.	.025-.250 (Max: 1/10 of Wheel Width)	A46HV
	Over 275	Quenched and Tempered	28 to 33	15 to 30	Rough: .050 Finish .013 max	1.25-12.5 (Max. 1/4 of Wheel Width)	A46HV

See section 16 for Cutting Fluid Recommendations.
*Wheel recommendations are for wet grinding. For DRY grinding—use a softer grade wheel. Also see section 20.2, Grinding Guidelines.

Surface Grinding-Horizontal Spindle, Reciprocating Table 8.1

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE SPEED fpm m/min	DOWNFEED in/pass mm/pass	CROSSFEED in/pass mm/pass	WHEEL* IDENTIFI-CATION ANSI ISO
19. PRECIPITATION HARDENING STAINLESS STEELS, CAST ASTM A351 Grade CD-4MCu ACI Grade CB-7Cu ACI Grade CD-4MCu 17-4 PH AM-355	325 to 450	Solution Treated or Solution Treated and Aged	5500 to 6500	50 to 100	Rough: .001 Finish .0005 max	.025-.250 (Max: 1/10 of Wheel Width)	A46HV
			28 to 33	15 to 30	Rough: .025 Finish .013 max.	.65-6.5 (Max: 1/10 of Wheel Width)	A46HV
21. GRAY CAST IRONS **Ferritic** ASTM A48: Class 20 SAE J431c: Grade G1800 **Pearlitic- Ferritic** ASTM A48: Class 25 SAE J431c: Grade G2500 **Pearlitic** ASTM A48: Classes 30, 35, 40 SAE J431c: Grade G3000 **Pearlitic + Free Carbides** ASTM A48: Classes 45, 50 SAE J431c. Grades G3500, G4000 **Pearlitic or Acicular + Free Carbides** ASTM A48: Classes 55, 60	45 R_C max	As Cast, Annealed or Quenched and Tempered	5500 to 6500	50 to 100	Rough: .003 Finish .001 max	.050-.500 (Max: 1/3 of Wheel Width)	C36JV or A46JV
			28 to 33	15 to 30	Rough: .075 Finish .025 max.	1.25-12.5 (Max: 1/3 of Wheel Width)	C36JV or A46JV
	45 R_C to 52 R_C	As Cast, Annealed or Quenched and Tempered	5500 to 6500	50 to 100	Rough: .002 Finish .0005 max.	.050-.500 (Max: 1/5 of Wheel Width)	C36IV or A46IV
			28 to 33	15 to 30	Rough: .050 Finish .013 max.	1.25-12.5 (Max: 1/5 of Wheel Width)	C36IV or A46IV
	48 R_C to 60 R_C	Flame or Induction Hardened	5500 to 6500	50 to 100	Rough: .002 Finish .0005 max.	.025-.250 (Max: 1/10 of Wheel Width)	C46HV or A46HV
			28 to 33	15 to 30	Rough: .050 Finish .013 max.	.65-6.5 (Max: 1/10 of Wheel Width)	C46HV or A46HV
Austenitic (NI-RESIST) ASTM A436. Types 1, 1b, 2, 2b, 3, 4, 5, 6	100 to 250	As Cast	5500 to 6500	50 to 100	Rough: .005 Finish .001 max.	.050-.500 (Max: 1/3 of Wheel Width)	Rough: A46HV Finish A80GV
			28 to 33	15 to 30	Rough: .13 Finish .025 max.	1.25-12.5 (Max: 1/3 of Wheel Width)	Rough: A46HV Finish A80GV
22. COMPACTED GRAPHITE CAST IRONS	185 to 255	As Cast	5500 to 6500	50 to 100	Rough: .003 Finish .001 max.	.050-.500 (Max: 1/3 of Wheel Width)	C36JV or A46IV
			28 to 33	15 to 30	Rough: .075 Finish .025 max.	1.25-12.5 (Max: 1/3 of Wheel Width)	C36JV or A46IV
23. DUCTILE CAST IRONS **Ferritic** ASTM A536: Grades 60-40-18, 65-45-12 SAE J434c: Grades D4018, D4512 **Ferritic- Pearlitic** ASTM A536: Grade 80-55-06 SAE J434c: Grade D5506 **Pearlitic- Martensitic** ASTM A536: Grade 100-70-03 SAE J434c: Grade D7003 **Martensitic** ASTM A536: Grade 120-90-02 SAE J434c: Grade DQ&T	52 R_C max.	Annealed, As Cast, Normalized and Tempered or Quenched and Tempered	5500 to 6500	50 to 100	Rough: .003 Finish .001 max.	.050-.500 (Max: 1/3 of Wheel Width)	C36IV or A46IV
			28 to 33	15 to 30	Rough: .075 Finish .025 max.	1.25-12.5 (Max: 1/3 of Wheel Width)	C36IV or A46IV
	53 R_C to 60 R_C	Flame or Induction Hardened	5500 to 6500	50 to 100	Rough: .002 Finish .0005 max.	.025-.250 (Max: 1/10 of Wheel Width)	C46HV or A46HV
			28 to 33	15 to 30	Rough: .050 Finish .013 max.	.65-6.5 (Max: 1/10 of Wheel Width)	C46HV or A46HV

See section 16 for Cutting Fluid Recommendations.
*Wheel recommendations are for wet grinding. For DRY grinding—use a softer grade wheel. Also see section 20.2, Grinding Guidelines

8.1 Surface Grinding-Horizontal Spindle, Reciprocating Table

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm / m/s	TABLE SPEED fpm / m/min	DOWNFEED in/pass / mm/pass	CROSSFEED in/pass / mm/pass	WHEEL* IDENTIFICATION ANSI / ISO
23. DUCTILE CAST IRONS (cont.) **Austenitic (NI-RESIST Ductile)** ASTM A439. Types D-2, D-2B, D-2C, D-3, D-3A, D-4, D-5, D-5B ASTM A571: Type D-2M	120 to 275	Annealed	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough .005 Finish .001 max. Rough: .13 Finish .025 max.	.050-.500 (Max. 1/3 of Wheel Width) 1.25-12.5 (Max. 1/3 of Wheel Width)	Rough: A46HV Finish A80GV Rough: A46HV Finish A80GV
24. MALLEABLE CAST IRONS **Ferritic** ASTM A47: Grades 32510, 35018 ASTM A602: Grade M3210 SAE J158: Grade M3210 **Pearlitic** ASTM A220: Grades 40010, 45006, 45008, 50005 ASTM A602: Grade M4504, M5003 SAE J158: Grades M4504, M5003 **Tempered Martensite** ASTM A220: Grades 60004, 70003, 80002, 90001 ASTM A602: Grades M5503, M7002, M8501 SAE J158: Grades M5503, M7002, M8501	52 R_C max.	Malleablized or Malleablized and Heat Treated	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .003 Finish .001 max. Rough: .075 Finish .025 max.	.050-.500 (Max: 1/3 of Wheel Width) 1.25-12.5 (Max: 1/3 of Wheel Width)	C36IV or A46IV C36IV or A46IV
	Over 52 R_C	Flame or Induction Hardened	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .002 Finish .0005 max. Rough: .050 Finish .013 max.	.025-.250 (Max: 1/10 of Wheel Width) .635-6.3 (Max: 1/10 of Wheel Width)	C46HV or A46HV C46HV or A46HV
25. WHITE CAST IRONS (ABRASION RESISTANT) ASTM A532: Class I, Types A, B, C, D Class II, Types A, B, C, D, E Class III, Type A	60 R_C max.	As Cast, Annealed or Hardened	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .002 Finish .0005 max. Rough: .050 Finish .013 max.	.025-.250 (Max: 1/10 of Wheel Width) .635-6.3 (Max: 1/10 of Wheel Width)	C36IV C36IV
26. HIGH SILICON CAST IRONS Duriron Duriclor ASTM A518	52 R_C	As Cast	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .002 Finish .0005 max. Rough: .050 Finish .013 max.	.025-.250 (Max: 1/10 of Wheel Width) .635-6.3 (Max: 1/10 of Wheel Width)	C46MB C46MB
27. CHROMIUM-NICKEL ALLOY CASTINGS ASTM A560: Grades 50Cr-50Ni, 60Cr-40Ni	275 to 375	As Cast	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .001 Finish .0005 max. Rough: .025 Finish .013 max.	.025-.250 (Max: 1/10 of Wheel Width) .635-6.3 (Max: 1/10 of Wheel Width)	C46HV C46HV

See section 16 for Cutting Fluid Recommendations.
*Wheel recommendations are for wet grinding. For DRY grinding—use a softer grade wheel. Also see section 20.2, Grinding Guidelines.

Surface Grinding-Horizontal Spindle, Reciprocating Table 8.1

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm / m/s	TABLE SPEED fpm / m/min	DOWNFEED in/pass / mm/pass	CROSSFEED in/pass / mm/pass	WHEEL* IDENTIFI-CATION ANSI / ISO
28. ALUMINUM ALLOYS, WROUGHT EC 2218 5252 6253 1060 2219 5254 6262 1100 2618 5454 6463 1145 3003 5456 6951 1175 3004 5457 7001 1235 3005 5652 7004 2011 4032 5657 7005 2014 5005 6053 7039 2017 5050 6061 7049 2018 5052 6063 7050 2021 5056 6066 7075 2024 5083 6070 7079 2025 5086 6101 7175 2117 5154 6151 7178	30 to 150 500kg	Cold Drawn or Solution Treated and Aged	4000 to 5000 20 to 25	50 to 100 15 to 30	Rough: .003 Finish .001 max Rough: .075 Finish .025 max	.050-.500 (Max: 1/3 of Wheel Width) 1.25-12.5 (Max: 1/3 of Wheel Width)	C46JV† C46JV†
29. ALUMINUM ALLOYS, CAST **Sand and Permanent Mold** A140 295.0 511.0 A712.0 201.0 B295.0 A514.0 D712.0 208.0 308.0 B514.0 713.0 213.0 319.0 520.0 771.0 222.0 355.0 535.0 850.0 224.0 C355.0 705.0 A850.0 242.0 B443.0 707.0 B850.0 Hiduminium RR-350 **Die Castings** C443.0 518.0	40 to 125 500kg	As Cast or Solution Treated and Aged	4000 to 5000 20 to 25	50 to 100 15 to 30	Rough: .003 Finish .001 max. Rough: .075 Finish .025 max.	.050-.500 (Max: 1/3 of Wheel Width) 1.25-12.5 (Max: 1/3 of Wheel Width)	C46JV† C46JV†
Sand and Permanent Mold 328.0 333.0 A356.0 A332.0 354.0 357.0 F332.0 356.0 359.0 **Die Castings** 360.0 A380.0 390.0 A413.0 A360.0 383.0 392.0 380.0 A384.0 413.0	40 to 125 500kg	As Cast or Solution Treated and Aged	4000 to 5000 20 to 25	50 to 100 15 to 30	Rough: .003 Finish .001 max. Rough: .075 Finish .025 max.	.050-.500 (Max: 1/3 of Wheel Width) 1.25-12.5 (Max: 1/3 of Wheel Width)	A46IV A46IV
30. MAGNESIUM ALLOYS, WROUGHT‡‡ AZ21A AZ61A HM21A ZK60A AZ31B AZ80A HM31A AZ31C HK31A ZK40A	50 to 90 500kg	Annealed, Cold Drawn or Solution Treated and Aged	5500 to 6500 20 to 25	50 to 100 15 to 30	Rough: .003 Finish .001 max. Rough: .075 Finish .025 max.	.050-.500 (Max: 1/3 of Wheel Width) 1.25-12.5 (Max: 1/3 of Wheel Width)	C46KV or A46KV C46KV or A46KV

See section 16 for Cutting Fluid Recommendations.
*Wheel recommendations are for wet grinding. For DRY grinding—use a softer grade wheel. Also see section 20.2, Grinding Guides.

†Wax filled
‡‡CAUTION: Potential Fire Hazard. Exercise caution in grinding and disposing of swarf. Do NOT use water or water-miscible cutting fluids for magnesium alloys.

8.1 Surface Grinding-Horizontal Spindle, Reciprocating Table

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE SPEED fpm m/min	DOWNFEED in/pass mm/pass	CROSSFEED in/pass mm/pass	WHEEL* IDENTIFI-CATION ANSI ISO
31. MAGNESIUM ALLOYS, CAST‡‡ AM60A AZ91C ZE41A AM100A AZ92A ZE63A AS41A EZ33A ZH62A AZ63A HK31A ZK51A AZ81A HZ32A ZK61A AZ91A K1A AZ91B QE22A	50 to 90 500kg	As Cast, Annealed or Solution Treated and Aged	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .003 Finish .001 max. Rough: .075 Finish .025 max.	.050-.500 (Max: 1/3 of Wheel Width) 1.25-12.5 (Max: 1/3 of Wheel Width)	C46KV or A46KV C46KV or A46KV
32. TITANIUM ALLOYS, WROUGHT‡‡ **Commercially Pure** 99.5 99.0 99.2 98.9 Ti-0.2Pd TiCODE-12	110 to 275	Annealed	3000 to 4000 15 to 20	60 18	Rough: .001 Finish .0005 max. Rough: .025 Finish .013 max.	.025-.250 (Max: 1/10 of Wheel Width) .65-6.5 (Max: 1/10 of Wheel Width)	C54JV‡ C54JV‡
Alpha and Alpha-Beta Alloys Ti-8Mn Ti-1Al-8V-5Fe Ti-2Al-11Sn-5Zr-1Mo Ti-3Al-2.5V Ti-5Al-2Sn-2Zr-4Mo-4Cr (Ti-17) Ti-5Al-2.5Sn Ti-5Al-2.5Sn ELI Ti-5Al-6Sn-2Zr-1Mo Ti-6Al-2Cb-1Ta-0.8Mo Ti-6Al-4V Ti-6Al-4V ELI Ti-6Al-6V-2Sn Ti-6Al-2Sn-4Zr-2Mo Ti-6Al-2Sn-4Zr-2Mo-.25Si Ti-6Al-2Sn-4Zr-6Mo Ti-7Al-4Mo Ti-8Al-1Mo-1V	300 to 380	Annealed	3000 to 4000 15 to 20	60 18	Rough: .001 Finish .0005 max. Rough: .025 Finish .013 max.	.025-.250 (Max: 1/10 of Wheel Width) .65-6.5 (Max: 1/10 of Wheel Width)	C54JV‡ C54JV‡
	320 to 440	Solution Treated and Aged	3000 to 4000 15 to 20	60 18	Rough: .001 Finish .0005 max. Rough: .025 Finish .013 max.	.025-.250 (Max: 1/10 of Wheel Width) .65-6.5 (Max: 1/10 of Wheel Width)	C54JV‡ C54JV‡
Beta Alloys Ti-3Al-8V-6Cr-4Mo-4Zr Ti-8Mo-8V-2Fe-3Al Ti-11.5Mo-6Zr-4.5Sn Ti-10V-2Fe-3Al Ti-13V-11Cr-3Al	275 to 350	Annealed or Solution Treated	3000 to 4000 15 to 20	60 18	Rough: .001 Finish .0005 max. Rough: .025 Finish .013 max.	.025-.250 (Max: 1/10 of Wheel Width) .65-6.5 (Max: 1/10 of Wheel Width)	C54JV‡ C54JV‡
	350 to 440	Solution Treated and Aged	3000 to 4000 15 to 20	60 18	Rough: .001 Finish .0005 max. Rough: .025 Finish .013 max.	.025-.250 (Max: 1/10 of Wheel Width) .65-6.5 (Max: 1/10 of Wheel Width)	C54JV‡ C54JV‡

See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding. For DRY grinding—use a softer grade wheel. Also see section 20.2, Grinding Guidelines

‡Use friable (green grit) silicon carbide

‡‡CAUTION: Potential Fire Hazard Exercise caution in grinding and disposing of swarf. Do NOT use water or water-miscible cutting fluids for magnesium alloys

Surface Grinding-Horizontal Spindle, Reciprocating Table 8.1

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm / m/s	TABLE SPEED fpm / m/min	DOWNFEED in/pass / mm/pass	CROSSFEED in/pass / mm/pass	WHEEL* IDENTIFI-CATION ANSI / ISO
33. TITANIUM ALLOYS, CAST‡‡ **Commercially Pure** 99.0 Ti-0.2Pd ASTM B367 Grades C-1, C-2, C-3, C-4, C-7A, C-7B, C-8A, C-8B	150 to 250	As Cast or As Cast and Annealed	3000 to 4000 15 to 20	60 18	Rough: .001 Finish .0005 max. Rough: .025 Finish .013 max.	.025-.250 (Max: 1/10 of Wheel Width) .65-6.5 (Max: 1/10 of Wheel Width)	C54JV‡ C54JV‡
Alpha and Alpha-Beta Alloys Ti-5Al-2 5Sn Ti-6Al-4V Ti-6Al-2Sn-4Zr-2Mo Ti-8Al-1Mo-1V ASTM B367: Grades C-5, C-6	300 to 350	As Cast or As Cast and Annealed	3000 to 4000 15 to 20	60 18	Rough: .001 Finish .0005 max. Rough: .025 Finish .013 max.	.025-.250 (Max: 1/10 of Wheel Width) .65-6.5 (Max: 1/10 of Wheel Width)	C54JV‡ C54JV‡
34. COPPER ALLOYS, WROUGHT 101 116 143 182 102 119 145 184 104 120 147 185 105 121 150 187 107 122 155 189 109 125 162 190 110 127 165 191 111 128 170†† 192 113 129 172†† 194 114 130 173†† 195 115 142 175††	10 R_B to 70 R_B	Annealed	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .003 Finish .0005 max. Rough: .075 Finish .013 max.	.050-.500 (Max: 1/3 of Wheel Width) 1.25-12.5 (Max: 1/3 of Wheel Width)	C36IV† C36IV†
	60 R_B to 100 R_B	Cold Drawn	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .003 Finish .0005 max. Rough: .075 Finish .013 max.	.050-.500 (Max: 1/3 of Wheel Width) 1.25-12.5 (Max: 1/3 of Wheel Width)	C36IV† C36IV†
210 332 368 464 220 335 370 465 226 340 377 466 230 342 385 467 240 349 411 482 260 350 413 485 268 353 425 667 270 356 435 687 280 360 442 688 314 365 443 694 316 366 444 330 367 445	10 R_B to 70 R_B	Annealed	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .003 Finish .0005 max. Rough: .075 Finish .013 max.	.050-.500 (Max: 1/3 of Wheel Width) 1.25-12.5 (Max: 1/3 of Wheel Width)	C36IV† C36IV†
	60 R_B to 100 R_B	Cold Drawn	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .003 Finish .0005 max. Rough: .075 Finish .013 max.	.050-.500 (Max: 1/3 of Wheel Width) 1.25-12.5 (Max: 1/3 of Wheel Width)	C36IV† C36IV†

See section 16 for Cutting Fluid Recommendations.
*Wheel recommendations are for wet grinding. For DRY grinding—use a softer grade wheel. Also see section 20.2, Grinding Guidelines.

†Wax filled.
‡Use friable (green grit) silicon carbide.
††CAUTION: Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions
‡‡CAUTION: Potential Fire Hazard. Exercise caution in grinding and disposing of swarf.

8.1 Surface Grinding-Horizontal Spindle, Reciprocating Table

MATERIAL	HARDNESS	CONDITION	WHEEL SPEED	TABLE SPEED	DOWNFEED	CROSSFEED	WHEEL* IDENTIFICATION
	Bhn		fpm m/s	fpm m/min	in/pass mm/pass	in/pass mm/pass	ANSI ISO
34. COPPER ALLOYS, WROUGHT (cont.) 505 608 623 642 510 610 624 651 511 613 625 655 521 614 630 674 524 618 632 675 544 619 638	10 R_B to 70 R_B	Annealed	5500 to 6500	50 to 100	Rough: .003 Finish .0005 max.	.050-.500 (Max: 1/3 of Wheel Width)	C36IV†
			28 to 33	15 to 30	Rough: .075 Finish .013 max.	1.25-12.5 (Max: 1/3 of Wheel Width)	C36IV†
	60 R_B to 100 R_B	Cold Drawn	5500 to 6500	50 to 100	Rough: .003 Finish .0005 max.	.050-.500 (Max: 1/3 of Wheel Width)	C36IV†
			28 to 33	15 to 30	Rough: .075 Finish .013 max.	1.25-12.5 (Max: 1/3 of Wheel Width)	C36IV†
706 752 710 754 715 757 725 770 745 782	10 R_B to 70 R_B	Annealed	5500 to 6500	50 to 100	Rough: .003 Finish .0005 max	.050-.500 (Max: 1/3 of Wheel Width)	C36IV†
			28 to 33	15 to 30	Rough: .075 Finish .013 max.	1.25-12.5 (Max: 1/3 of Wheel Width)	C36IV†
	60 R_B to 100 R_B	Cold Drawn	5500 to 6500	50 to 100	Rough: .003 Finish .0005 max.	.050-.500 (Max: 1/3 of Wheel Width)	C36IV†
			28 to 33	15 to 30	Rough: .075 Finish .013 max.	1.25-12.5 (Max: 1/3 of Wheel Width)	C36IV†
35. COPPER ALLOYS, CAST 801 811 818†† 825†† 803 813 820†† 826†† 805 814 821†† 827†† 807 815 822†† 828†† 809 817†† 824††	40 to 200 500kg	As Cast or Heat Treated	5500 to 6500	50 to 100	Rough: .003 Finish .0005 max.	.050-.500 (Max: 1/3 of Wheel Width)	C36IV†
			28 to 33	15 to 30	Rough: .075 Finish .013 max.	1.25-12.5 (Max: 1/3 of Wheel Width)	C36IV†
	34 R_C to 45 R_C	Heat Treated	5500 to 6500	50 to 100	Rough: .003 Finish .0005 max.	.050-.500 (Max: 1/3 of Wheel Width)	A46JV
			28 to 33	15 to 30	Rough: .075 Finish .013 max.	1.25-12.5 (Max: 1/3 of Wheel Width)	A46JV
833 852 862 874 834 853 863 875 836 854 864 876 838 855 865 878 842 857 867 879 844 858 868 848 861 872	35 to 200 500kg	As Cast	5500 to 6500	50 to 100	Rough: .003 Finish .0005 max.	.050-.500 (Max: 1/3 of Wheel Width)	C36IV†
			28 to 33	15 to 30	Rough: .075 Finish .013 max.	1.25-12.5 (Max: 1/3 of Wheel Width)	C36IV†
902 916 934 948 903 917 935 952 905 922 937 953 907 923 938 954 909 925 939 955 910 926 943 956 911 927 944 957 913 928 945 958 915 932 947	40 to 100 500kg	As Cast	5500 to 6500	50 to 100	Rough: .003 Finish .0005 max	.050-.500 (Max: 1/3 of Wheel Width)	C36IV†
			28 to 33	15 to 30	Rough: .075 Finish .013 max.	1.25-12.5 (Max: 1/3 of Wheel Width)	C36IV†
	Over 100 500kg	As Cast or Heat Treated	5500 to 6500	50 to 100	Rough: .003 Finish .0005 max.	.050-.500 (Max: 1/3 of Wheel Width)	A46JV
			28 to 33	15 to 30	Rough: .075 Finish .013 max.	1.25-12.5 (Max: 1/3 of Wheel Width)	A46JV

See section 16 for Cutting Fluid Recommendations.
*Wheel recommendations are for wet grinding. For DRY grinding—use a softer grade wheel. Also see section 20.2, Grinding Guidelines.

†Wax filled.
††CAUTION: Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions

Surface Grinding-Horizontal Spindle, Reciprocating Table 8.1

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm	TABLE SPEED fpm	DOWNFEED in/pass	CROSSFEED in/pass	WHEEL* IDENTIFI-CATION ANSI
			m/s	m/min	mm/pass	mm/pass	ISO
962 974 963 976 964 978 966†† 993 973	50 to 100 500kg	As Cast	5500 to 6500	50 to 100	Rough: .003 Finish .0005 max.	.050-.500 (Max: 1/3 of Wheel Width)	C36IV†
			28 to 33	15 to 30	Rough: .075 Finish .013 max.	1.25-12.5 (Max: 1/3 of Wheel Width)	C36IV†
	Over 100 500kg	As Cast or Heat Treated	5500 to 6500	50 to 100	Rough: 003 Finish .0005 max.	.050-.500 (Max: 1/3 of Wheel Width)	A46JV
			28 to 33	15 to 30	Rough: .075 Finish .013 max.	1.25-12.5 (Max: 1/3 of Wheel Width)	A46JV
36. NICKEL ALLOYS, WROUGHT AND CAST Nickel 200 Nickel 201 Nickel 205 Nickel 211 Nickel 220 Nickel 230	80 to 170	Annealed or Cold Drawn	4500 to 5500	50 to 100	Rough: .001 Finish .0005 max	.040-.400 (Max. 1/6 of Wheel Width)	A46IV
			23 to 28	15 to 30	Rough: .025 Finish .013 max.	1.0-10.0 (Max: 1/6 of Wheel Width)	A46IV
MONEL Alloy 400 MONEL Alloy 401 MONEL Alloy 404 MONEL Alloy R405 ASTM A296: Grades CZ-100, M-35 ASTM A494: Grades CZ-100, M-35	115 to 240	Annealed, Cold Drawn or Cast	5500 to 6500	50 to 100	Rough: .001 Finish .0005 max.	.040-.400 (Max: 1/6 of Wheel Width)	A46IV
			28 to 33	15 to 30	Rough: .075 Finish .013 max.	1.0-10.0 (Max: 1/6 of Wheel Width)	A46IV
DURANICKEL Alloy 301 MONEL Alloy 502 MONEL Alloy K500 NI-SPAN-C Alloy 902 PERMANICKEL Alloy 300	150 to 320	Solution Treated	5500 to 6500	50 to 100	Rough: .001 Finish .0005 max.	.040-.400 (Max: 1/6 of Wheel Width)	A60IV
			28 to 33	15 to 30	Rough: .075 Finish .013 max.	1.0-10.0 (Max: 1/6 of Wheel Width)	A60IV
	330 to 360	Aged	5500 to 6500	50 to 100	Rough: .001 Finish .0005 max.	.040-.400 (Max: 1/6 of Wheel Width)	A60IV
			28 to 33	15 to 30	Rough: .075 Finish .013 max.	1.0-10.0 (Max: 1/6 of Wheel Width)	A60IV
37. BERYLLIUM NICKEL ALLOYS, WROUGHT AND CAST†† Beryico 440 Beryico 41C Beryico 42C Beryico 43C Brush Alloy 200C Brush Alloy 220C Brush Alloy 260C	200 to 250	As Cast or Solution Treated	5000 to 6000	35	Rough: .001 Finish .0005 max.	.040-.400 (Max: 1/6 of Wheel Width)	A46IV
			25 to 30	10 to 15	Rough: .075 Finish .013 max.	1.0-10.0 (Max: 1/6 of Wheel Width)	A46IV
	283 to 425	Hardened or Aged	5000 to 6000	35	Rough: .001 Finish .0005 max.	.040-.400 (Max: 1/6 of Wheel Width)	A46HV
			25 to 30	10 to 15	Rough: .075 Finish .013 max.	1.0-10.0 (Max: 1/6 of Wheel Width)	A46HV

See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding. For DRY grinding—use a softer grade wheel Also see section 20.2, Grinding Guidelines.

†Wax filled.

††CAUTION: Toxic Material, refer to National Institute for Occupational Safety and Health, (NIOSH) for Precautions.

8.1 Surface Grinding-Horizontal Spindle, Reciprocating Table

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm / m/s	TABLE SPEED fpm / m/min	DOWNFEED in/pass / mm/pass	CROSSFEED in/pass / mm/pass	WHEEL* IDENTIFI-CATION ANSI / ISO
37. BERYLLIUM NICKEL ALLOYS, WROUGHT AND CAST†† (cont.) (materials listed on preceding page)	47 R_C to 52 R_C	Hardened or Aged	5000 to 6000	35	Rough: .001 Finish .0005 max.	.040-.400 (Max: 1/6 of Wheel Width)	A60GV
			25 to 30	11	Rough: .025 Finish .013 max.	1.0-10.0 (Max: 1/6 of Wheel Width)	A60GV
38. NITINOL ALLOYS, WROUGHT Nitinol 55Ni-45Ti Nitinol 56Ni-44Ti Nitinol 60Ni-40Ti	210 to 340	Wrought or Annealed	5000	40	Rough: .002 Finish .0005 max.	.025-.250 (Max: 1/10 of Wheel Width)	C60IV
			25	12	Rough: .050 Finish .013 max.	.65-6.5 (Max: 1/10 of Wheel Width)	C60IV
	48 R_C to 52 R_C	Quenched	5000	40	Rough: .002 Finish .0005 max.	.025-.250 (Max: 1/10 of Wheel Width)	C60IV
			25	12	Rough: .050 Finish .013 max.	.65-6.5 (Max: 1/10 of Wheel Width)	C60IV
39. HIGH TEMPERATURE ALLOYS, WROUGHT AND CAST **Nickel Base, Wrought** AF2-1DA Astroloy Haynes Alloy 263 IN-102 Incoloy Alloy 901 Incoloy Alloy 903 Inconel Alloy 617 Inconel Alloy 625 Inconel Alloy 700 Inconel Alloy 702 Inconel Alloy 706 Inconel Alloy 718 Inconel Alloy 721 Inconel Alloy 722 Inconel Alloy X-750 Inconel Alloy 751 M252 Nimonic 75 Nimonic 80 Nimonic 90 Nimonic 95 Rene 41 Rene 62 Rene 77 Rene 95 Udimet 500 Udimet 700 Udimet 710 Unitemp 1753 Waspaloy	200 to 390	Annealed or Solution Treated	3000 to 3500	50 to 100	Rough: .001 Finish .0005 max.	.020-.200 (Max: 1/12 of Wheel Width)	A46HV
			15 to 25	15 to 30	Rough: .025 Finish .013 max.	.50-5.0 (Max: 1/12 of Wheel Width)	A46HV
	300 to 475	Solution Treated and Aged	3000 to 3500	50 to 100	Rough: .001 Finish .0005 max.	.020-.200 (Max: 1/12 of Wheel Width)	A46HV
			15 to 25	15 to 30	Rough: .025 Finish .013 max.	.50-5.0 (Max: 1/12 of Wheel Width)	A46HV

See section 16 for Cutting Fluid Recommendations.

*Wheel recommendations are for wet grinding. For DRY grinding—use a softer grade wheel. Also see section 20.2, Grinding Guidelines.

††CAUTION: Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions.

Surface Grinding-Horizontal Spindle, Reciprocating Table 8.1

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE SPEED fpm m/min	DOWNFEED in/pass mm/pass	CROSSFEED in/pass mm/pass	WHEEL* IDENTIFI-CATION ANSI ISO
Nickel Base, Wrought Hastelloy Alloy B Hastelloy Alloy B-2 Hastelloy Alloy C Hastelloy Alloy C-276 Hastelloy Alloy G Hastelloy Alloy S Hastelloy Alloy X Incoloy Alloy 804 Incoloy Alloy 825 Inconel Alloy 600 Inconel Alloy 601 Refractaloy 26 Udimet 630	140 to 220	Annealed or Solution Treated	3000 to 4000	50 to 100	Rough: .001 Finish .0005 max.	.025-.250 (Max: 1/10 of Wheel Width)	A46HV
			15 to 20	15 to 30	Rough: .025 Finish .013 max.	.65-6.5 (Max: 1/10 of Wheel Width)	A46HV
	240 to 310	Cold Drawn or Aged	3000 to 4000	50 to 100	Rough: .001 Finish .0005 max	.025-.250 (Max 1/10 of Wheel Width)	A46HV
			15 to 20	15 to 30	Rough: .025 Finish .013 max.	.65-6.5 (Max: 1/10 of Wheel Width)	A46HV
Nickel Base, Wrought TD-Nickel†† TD-Ni-Cr††	180 to 200	As Rolled	5500 to 6500	50 to 100	Rough: .002 Finish .0005 max	.050-.500 (Max 1/4 of Wheel Width)	A46HV
			28 to 33	15 to 30	Rough: .050 Finish .013 max.	1.25-12.5 (Max: 1/4 of Wheel Width)	A46HV
Nickel Base, Cast B-1900 GMR-235 GMR-235D Hastelloy Alloy B Hastelloy Alloy C Hastelloy Alloy D IN-100 (Rene 100) IN-738 IN-792 Inconel Alloy 713C Inconel Alloy 718 M252 MAR-M200 MAR-M246 MAR-M421 MAR-M432 Rene 80 Rene 125 SEL SEL 15 TRW VI A Udimet 500 Udimet 700 ASTM A217: Grades CW-12M, N-12M, CY-40 ASTM A297: Grades HW, HX ASTM A494: Grades N-12M-1, N-12M-2, CY-40, CW-12M-1, CW-12M-2 ASTM A608: Grades HW50, HX50	200 to 425	As Cast or Cast and Aged	3000 to 3500	50 to 100	Rough: .001 Finish .0005 max.	.020-.200 (Max: 1/12 of Wheel Width)	A46HV
			15 to 18	15 to 30	Rough: .025 Finish .013 max.	.50-5.0 (Max: 1/12 of Wheel Width)	A46HV

See section 16 for Cutting Fluid Recommendations.

*Wheel recommendations are for wet grinding. For DRY grinding—use a softer grade wheel. Also see section 20.2, Grinding Guidelines.

††CAUTION: Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions.

8.1 Surface Grinding-Horizontal Spindle, Reciprocating Table

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE SPEED fpm m/min	DOWNFEED in/pass mm/pass	CROSSFEED in/pass mm/pass	WHEEL* IDENTIFI-CATION ANSI ISO
39. HIGH TEMPERATURE ALLOYS, WROUGHT AND CAST (cont.)	180 to 230	Solution Treated	3000 to 3500	50 to 100	Rough: .001 Finish .0005 max.	.020-.200 (Max: 1/12 of Wheel Width)	A46HV
			15 to 18	15 to 30	Rough: .025 Finish .013 max.	.50-5.0 (Max: 1/12 of Wheel Width)	A46HV
Cobalt Base, Wrought AiResist 213 Haynes Alloy 25 (L605) Haynes Alloy 188 J-1570 MAR-M905 MAR-M918 S-816 V-36	270 to 320	Solution Treated and Aged	3000 to 3500	50 to 100	Rough: .001 Finish .0005 max.	.020-.200 (Max: 1/12 of Wheel Width)	A46HV
			15 to 18	15 to 30	Rough: .025 Finish .013 max.	.50-5.0 (Max: 1/12 of Wheel Width)	A46HV
Cobalt Base, Cast AiResist 13 AiResist 215 FSX-414 HS-6 HS-21 HS-31 (X-40) HOWMET #3 MAR-M302 MAR-M322 MAR-M509 NASA Co-W-Re WI 52 X-45	220 to 290	As Cast or Cast and Aged	3000 to 3500	50 to 100	Rough: .001 Finish .0005 max.	.020-.200 (Max: 1/12 of Wheel Width)	A46HV
			15 to 18	15 to 30	Rough: .025 Finish .013 max.	.50-5.0 (Max: 1/12 of Wheel Width)	A46HV
	290 to 425	As Cast or Cast and Aged	3000 to 3500	50 to 100	Rough: .001 Finish .0005 max.	.020-.200 (Max: 1/12 of Wheel Width)	A46HV
			15 to 18	15 to 30	Rough: .025 Finish .013 max.	.50-5.0 (Max: 1/12 of Wheel Width)	A46HV
Iron Base, Wrought A-286 Discaloy Incoloy Alloy 800 Incoloy Alloy 800H Incoloy Alloy 801 Incoloy Alloy 802 N-155 V-57 W-545 16-25-6 19-9DL	180 to 230	Solution Treated	3000 to 4000	50 to 100	Rough: .001 Finish .0005 max.	.025-.250 (Max: 1/10 of Wheel Width)	A46HV
			15 to 18	15 to 30	Rough: .025 Finish .013 max.	.50-5.0 (Max: 1/12 of Wheel Width)	A46HV
	250 to 320	Solution Treated and Aged	3000 to 4000	50 to 100	Rough: .001 Finish .0005 max.	.025-.250 (Max: 1/10 of Wheel Width)	A46HV
			15 to 18	15 to 30	Rough: .025 Finish .013 max.	.50-5.0 (Max: 1/12 of Wheel Width)	A46HV
40. REFRACTORY ALLOYS, WROUGHT, CAST, P/M** **Columbium** †† ‡‡** C103 C129Y Cb-1Zr Cb-752 FS-85 FS-291 WC-3015	170 to 225	Stress Relieved	2000 to 4000	40 to 60	Rough: .001 Finish .0005 max.	.020-.200 (Max: 1/12 of Wheel Width)	A46JV
			15 to 18	15 to 30	Rough: .025 Finish .013 max.	.50-5.0 (Max: 1/12 of Wheel Width)	A46JV
Molybdenum** Mo Mo-50Re TZC TZM	220 to 290	Stress Relieved	2000 to 4000	20 to 40	Rough: .001 Finish .0005 max.	.020-.200 (Max: 1/12 of Wheel Width)	A46KV
			15 to 18	15 to 30	Rough: .025 Finish .013 max.	.50-5.0 (Max: 1/12 of Wheel Width)	A46KV

See section 16 for Cutting Fluid Recommendations.

*Wheel recommendations are for wet grinding. For DRY grinding—use a softer grade wheel. Also see section 20.2, Grinding Guidelines

**Due to the brittleness of refractory alloys, cracking, chipping, flaking and breakout tend to occur, particularly on the edges of the machined surfaces.

††CAUTION: Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions

‡‡CAUTION: Potential Fire Hazard. Exercise caution in grinding and disposing of swarf.

Surface Grinding-Horizontal Spindle, Reciprocating Table 8.1

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE SPEED fpm m/min	DOWNFEED in/pass mm/pass	CROSSFEED in/pass mm/pass	WHEEL* IDENTIFI-CATION ANSI ISO
Tantalum** ASTAR 811C T-111 T-222 Ta-10W Ta-Hf Ta63	200 to 250	Stress Relieved	2000 to 4000	40	Rough: .001 Finish .0005 max.	.020-.200 (Max: 1/12 of Wheel Width)	A46JV
			10 to 20	12	Rough: .025 Finish .013 max.	.50-5.0 (Max: 1/12 of Wheel Width)	A46JV
Tungsten** 85% density 93% density 96% density 100% density	180 to 320	Pressed and Sintered, Forged, or Arc Cast	2000	40 to 60	Rough: .001 Finish .0005 max.	.020-.200 (Max: 1/12 of Wheel Width)	A46NV or C36JV
			10	12 to 18	Rough: .025 Finish .013 max.	.50-5.0 (Max: 1/12 of Wheel Width)	A46NV or C36JV
Tungsten - 2 Thoria** ††	260 to 320	Pressed and Sintered	2000	40 to 60	Rough: .001 Finish .0005 max.	.020-.200 (Max: 1/12 of Wheel Width)	C60JV
			10	12 to 18	Rough: .025 Finish .013 max.	.50-5.0 (Max: 1/12 of Wheel Width)	C60JV
Tungsten Alloys** GE-218 W-15Mo W-5Re W-25Re W-25Re-30Mo	260 to 320	As Cast	2000	40 to 60	Rough: .001 Finish .0005 max.	.020-.200 (Max: 1/12 of Wheel Width)	C60JV
			10	12 to 18	Rough: .025 Finish .013 max.	.50-5.0 (Max: 1/12 of Wheel Width)	C60JV
Tungsten Alloys** Gyromet Mallory 2000 W-10Ag W-7Ni-4Cu	290 to 320	Pressed and Sintered	2000	40 to 60	Rough: .001 Finish .0005 max.	.020-.200 (Max: 1/12 of Wheel Width)	C60JV
			10	12 to 18	Rough: .025 Finish .013 max.	.50-5.0 (Max: 1/12 of Wheel Width)	C60JV
Tungsten Alloys** Anviloy 1100 Anviloy 1150 Anviloy 1200	290 to 320	Pressed and Sintered	4000	40 to 60	Rough: .001 Finish .0005 max.	.020-.200 (Max: 1/12 of Wheel Width)	C60JV
			10	12 to 18	Rough: .025 Finish .013 max.	.50-5.0 (Max: 1/12 of Wheel Width)	C60JV
44. URANIUM, WROUGHT†† ‡‡	56 R_A to 58 R_A	Annealed	3000 to 5000	50 to 75	Rough: .005 Finish .002 max.	.025-.250 (Max: 1/10 of Wheel Width)	C46GV
			15	18 to 23	Rough: .125 Finish .050 max.	.625-6.25 (Max: 1/10 of Wheel Width)	C46GV

See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding. For DRY grinding—use a softer grade wheel. Also see section 20.2, Grinding Guidelines.

**Due to the brittleness of refractory alloys, cracking, chipping, flaking and breakout tend to occur, particularly on the edges of the machined surfaces

††CAUTION: Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions

‡‡CAUTION. Potential Fire Hazard. Exercise caution in grinding and disposing of swarf.

8.1 Surface Grinding-Horizontal Spindle, Reciprocating Table

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE SPEED fpm m/min	DOWNFEED in/pass mm/pass	CROSSFEED in/pass mm/pass	WHEEL* IDENTIFI-CATION ANSI ISO
45. ZIRCONIUM ALLOYS, WROUGHT‡‡ Zr-2%Hf (Grade 11) Zr-0.001%Hf (Grade 21) Zircaloy 2 (Grade 32) Zircaloy 4 (Grade 34)	140 to 280	Rolled, Extruded or Forged	3000 15	40 12	Rough .001 Finish .0005 max. Rough: .025 Finish .013 max.	.040-.100 (Max: 1/6 of Wheel Width) 1.0-10.0 (Max: 1/6 of Wheel Width)	C46JV C46JV
47. POWDER METAL ALLOYS** **Copper**** CZP-0218-T CZP-0218-U CZP-0218-W 90Cu-10Zn 90Cu-10Zn-0.5Pb 70Cu-30Zn 68.5Cu-30Zn-1.5Pb	50 R_F to 70 R_F	As Sintered	5500 to 6500 28 to 33	50 to 100 15 to 20	Rough: .003 Finish .0005 max. Rough: .075 Finish .013 max.	.050-.500 (Max: 1/3 of Wheel Width) 1.25-12.5 (Max: 1/3 of Wheel Width)	C36IV† C36IV†
Brasses** CZP-0218-T CZP-0218-U CZP-0218-W 90Cu-10Zn 90Cu-10Zn-0.5Pb 70Cu-30Zn 68.5Cu-30Zn-1.5Pb	35 R_H to 81 R_H	As Sintered	5500 to 6500 28 to 33	50 to 100 15 to 20	Rough: .003 Finish .0005 max. Rough: .075 Finish .013 max.	.050-.500 (Max: 1/3 of Wheel Width) 1.25-12.5 (Max: 1/3 of Wheel Width)	C36IV† C36IV†
Bronzes** CT-0010-N CT-0010-R CT-0010-S 95Cu-5Al 77Cu-15Pb-7Sn-1Fe-1C	30 R_F to 75 R_F	As Sintered	5500 to 6500 28 to 33	50 to 100 15 to 20	Rough: .003 Finish .0005 max. Rough: .075 Finish .013 max.	.050-.500 (Max: 1/3 of Wheel Width) 1.25-12.5 (Max: 1/3 of Wheel Width)	C36IV† C36IV†
Copper-Nickel Alloys** CZN-1818-T CZN-1818-U CZN-1818-W CZNP-1618-U CZNP-1618-W 90Cu-10Ni 62Cu-18Ni-18Zn-2Sn	22 R_H to 100 R_H	As Sintered	5500 to 6500 28 to 33	50 to 100 15 to 20	Rough: .003 Finish .0005 max. Rough: .075 Finish .013 max.	.050-.500 (Max: 1/3 of Wheel Width) 1.25-12.5 (Max: 1/3 of Wheel Width)	C36IV† C36IV†
Nickel** [illegible]	45 R_B	As Sintered	4500 to 5500 23 to 28	50 to 100 15 to 20	Rough: .001 Finish .0005 max. Rough: .025 Finish .013 max.	.040-.400 (Max: 1/6 of Wheel Width) 1.0-10.0 (Max: 1/6 of Wheel Width)	A60IV A60IV

See section 16 for Cutting Fluid Recommendations.

*Wheel recommendations are for wet grinding. For DRY grinding—use a softer grade wheel. Also see section 20.2, Grinding Guidelines.

†Wax filled

**Grinding of low-density parts is not recommended because surface porosity will be reduced or lost.

‡‡CAUTION. Potential Fire Hazard. Exercise caution in grinding and disposing of swarf.

Surface Grinding-Horizontal Spindle, Reciprocating Table 8.1

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE SPEED fpm m/min	DOWNFEED in/pass mm/pass	CROSSFEED in/pass mm/pass	WHEEL* IDENTIFI-CATION ANSI ISO
Nickel Alloys**			5500 to 6500	50 to 100	Rough. 001 Finish .0005 max.	.040-.400 (Max: 1/6 of Wheel Width)	A46IV
67Ni-30Cu-3Fe	34 R_B to 50 R_B	As Sintered	28 to 33	15 to 30	Rough: .025 Finish .013 max.	1.0-10.0 (Max: 1/6 of Wheel Width)	A46IV
Refractory Metal Base**			2000	50 to 100	Rough .001 Finish .0005 max.	.020-.200 (Max: 1/12 of Wheel Width)	C60JV
87W-13Cu 85W-15Ag 74W-26Cu 72.5W-27.5Ag 65W-35Ag 56W+C-44Cu 55W-45Cu 51W-49Ag 50W+C-50Ag	101 to 260	As Sintered	10	15 to 30	Rough: .025 Finish .013 max.	.50-5.0 (Max: 1/12 of Wheel Width)	C60JV
Refractory Metal Base**			4000	40 to 80	Rough: 001 Finish .0005 max	.020-.200 (Max: 1/12 of Wheel Width)	A46KV
61Mo-39Ag 50Mo-50Ag	75 R_B to 82 R_B	As Sintered	20	12 to 24	Rough: .025 Finish .013 max.	.50-5.0 (Max: 1/12 of Wheel Width)	A46KV
Irons**			1700 to 2000	50 to 100	Rough: .002 Finish .0005 max.	.050-.500 (Max: 1/4 of Wheel Width)	C36IV or A46IV
F-0000-N F-0000-P F-0000-R F-0000-S F-0000-T	50 to 67 500kg	As Sintered	8.5 to 10	15 to 30	Rough: .050 Finish .013 max.	1.25-12.5 (Max: 1/4 of Wheel Width)	C36IV or A46IV
Steels**			5500 to 6500	50 to 100	Rough: .003 Finish .0005 max.	.050-.500 (Max: 1/4 of Wheel Width)	A46JV
F-0008-P F-0008-S F-0005-S FC-0205-S FC-0208-P FC-0208-S FC-0508-P FC-1000-N FN-0205-S FN-0205-T FN-0405-R FN-0405-S FN-0405-T FX-1005-T FX-2008-T	101 to 426	As Sintered or Heat Treated	28 to 33	15 to 30	Rough: .025 Finish .013 max.	1.25-12.5 (Max: 1/4 of Wheel Width)	A46JV
Stainless Steels**			5500 to 6500	50 to 100	Rough. .002 Finish .0005 max.	.050-.500 (Max: 1/4 of Wheel Width)	C46JV
SS-303-R SS-304-R SS-316-R SS-410-R	107 to 285	As Sintered or Heat Treated	28 to 33	15 to 30	Rough: .025 Finish .013 max.	1.25-12.5 (Max: 1/4 of Wheel Width)	C46JV

See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding. For DRY grinding—use a softer grade wheel. Also see section 20.2, Grinding Guidelines.

**Grinding of low-density parts is not recommended because surface porosity will be reduced or lost.

8.1 Surface Grinding-Horizontal Spindle, Reciprocating Table

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE SPEED fpm m/min	DOWNFEED in/pass mm/pass	CROSSFEED in/pass mm/pass	WHEEL* IDENTIFI-CATION ANSI ISO
47. POWDER METAL ALLOYS (cont.) **Aluminum Alloys**** 90.5Al-5Sn-4Cu 88Al-5Sn-4Pb-3Cu Al-1Mg-0.6Si-0.25Cu Al-0.6Mg-0.4Si Al-4.4Cu-0.8Si-0.4Mg	55 R_H to 98 R_H	Solution Treated and Aged	4000 to 5000	50 to 100	Rough: .003 Finish .001 max.	.050-.500 (Max 1/3 of Wheel Width)	C46JV†
			20 to 25	15 to 30	Rough: .075 Finish .025 max.	1.25-12.5 (Max. 1/3 of Wheel Width)	C46JV†
48. MACHINABLE CARBIDES Ferro-Tic	40 R_C to 51 R_C	Annealed	5500 to 6500	50 to 60	Rough: .002 Finish .001 max.	.010-.060 (Max. 1/12 of Wheel Width)	Rough: A46FV Finish A80GV
			29 to 33	15 to 18	Rough: .050 Finish .025 max.	.25-1.5 (Max. 1/12 of Wheel Width)	Rough: A46FV Finish A80GV
	68 R_C to 70 R_C	Hardened and Tempered	5500 to 6500	50 to 60	Rough: .002 Finish .0005 max.	.010-.060 (Max: 1/12 of Wheel Width)	C46FV or A80GV
			29 to 33	15 to 18	Rough: .050 Finish .013 max.	.25-1.5 (Max. 1/12 of Wheel Width)	C46FV or A80GV
49. CARBIDES Titanium Carbide Tungsten Carbide	83 R_A to 94 R_A	—	5000 to 6000	30 to 50	Rough: .001 Finish .0005 max.	.030-.060 (Max: 1/12 of Wheel Width)	Rough C60GV Finish C100FV‡
			25 to 29	9 to 15	Rough: .025 Finish .013 max.	.75-1.5 (Max. 1/12 of Wheel Width)	Rough C60GV Finish C100FV‡
50. FREE MACHINING MAGNETIC ALLOYS Magnetic Core Iron-FM (up to 2.5% Si)	185 to 240	Wrought	5500 to 6500	50 to 100	Rough: .003 Finish .001 max.	.050-.500 (Max: 1/3 of Wheel Width)	A46JV
			48 to 50	15 to 30	Rough: .075 Finish .025 max.	1.25-12.5 (Max. 1/3 of Wheel Width)	A46JV
Hi Perm 49-FM	185 to 240	Wrought	5500 to 6500	50 to 100	Rough: .002 Finish .0005 max.	.50-.500 (Max. 1/4 of Wheel Width)	C46JV
			48 to 50	15 to 30	Rough: .050 Finish .013 max.	.25-1.25 (Max. 1/4 of Wheel Width)	C46JV
51. MAGNETIC ALLOYS Magnetic Core Iron (up to 4% Si)	185 to 240	Wrought	5500 to 6500	50 to 100	Rough: .003 Finish .001 max.	.050-.500 (Max: 1/3 of Wheel Width)	A46JV
			48 to 50	15 to 30	Rough: .075 Finish .025 max.	1.25-12.5 (Max. 1/3 of Wheel Width)	A46JV
Hi Perm 49 HyMu 80	185 to 240	Wrought	5500 to 6500	50 to 100	Rough: .002 Finish .0005 max.	.050-.500 (Max: 1/4 of Wheel Width)	C46JV
			48 to 50	15 to 30	Rough: .050 Finish .013 max.	.25-1.25 (Max. 1/4 of Wheel Width)	C46JV

See section 16 for Cutting Fluid Recommendations.
*Wheel recommendations are for wet grinding. For DRY grinding—use a softer grade wheel. Also see section 20.2, Grinding Guidelines.

†Wax filled.
‡Diamond wheel is preferable, see section 8.3.
**Grinding of low-density parts is not recommended because surface porosity will be reduced or lost

Surface Grinding-Horizontal Spindle, Reciprocating Table 8.1

MATERIAL	HARDNESS Bhn	CONDITION	WHEEL SPEED fpm / m/s	TABLE SPEED fpm / m/min	DOWNFEED in/pass / mm/pass	CROSSFEED in/pass / mm/pass	WHEEL* IDENTIFICATION ANSI / ISO
Alnico I Alnico II Alnico III Alnico IV Alnico V Alnico V-7 Alnico XII Columax-5 Hyflux Alnico V-7	45 R_C to 58 R_C	As Cast	5500 to 6500 28 to 33	30 9	Rough: .002 Finish .0005 max. Rough: .050 Finish .013 max.	.015 (Max: 1/10 of Wheel Width) 40 (Max: 1/10 of Wheel Width)	A54GV§ A54GV§
52. FREE MACHINING CONTROLLED EXPANSION ALLOYS Invar 36	125 to 220	Annealed or Cold Drawn	3000 to 4000 15 to 20	50 to 100 15 to 30	Rough: .001 Finish .0005 max. Rough: .025 Finish .013 max.	.040-.400 (Max: 1/6 of Wheel Width) 1.0-10.0 (Max: 1/6 of Wheel Width)	C46JV C46JV
53. CONTROLLED EXPANSION ALLOYS Invar Kovar	125 to 250	Annealed or Cold Drawn	3000 to 4000 15 to 20	50 to 100 15 to 30	Rough: .001 Finish .0005 max. Rough: .025 Finish .013 max.	.040-.400 (Max: 1/6 of Wheel Width) 1.0-10.0 (Max: 1/6 of Wheel Width)	C46JV C46JV
54. CARBONS & GRAPHITES Mechanical Grades	40 to 100 Shore	Molded or Extruded	5500 to 6500 28 to 33	50 to 60 15 to 18	Rough: .010 Finish .003 max. Rough: .25 Finish .075 max.	.025-.250 (Max: 1/10 of Wheel Width) .64-6.4 (Max: 1/10 of Wheel Width)	C36KV C36KV
Brush Grade Carbon	8 to 90 Shore	Molded or Extruded	5500 to 6500 28 to 33	50 to 60 15 to 18	Rough: .010 Finish .003 max. Rough: .25 Finish .075 max.	.025-.250 (Max: 1/10 of Wheel Width) .64-6.4 (Max: 1/10 of Wheel Width)	C36KV C36KV
Graphite	—	—	5500 to 6500 28 to 33	50 to 60 15 to 18	Rough: .010 Finish .003 max. Rough: .25 Finish .075 max.	.025-.250 (Max: 1/10 of Wheel Width) .64-6.4 (Max: 1/10 of Wheel Width)	Rough: C36IV Finish C60IV Rough: C36IV Finish C60IV
55. GLASSES & CERAMICS PYROCERAM	700 Knoop 100g	—	4000 to 6000 20 to 30	20 to 40 6 to 12	Rough: .003 Finish .001 max. Rough: .075 Finish .025 max.	.020-.100 (Max: 1/12 of Wheel Width) .5-2.5 (Max: 1/12 of Wheel Width)	C60JV C60JV
Glass	480 to 530 Knoop 100g	—	4000 to 6000 20 to 30	20 to 40 6 to 12	Rough: .003 Finish .001 max. Rough: .075 Finish .025 max.	.020-.100 (Max: 1/10 of Wheel Width) .5-2.5 (Max: 1/10 of Wheel Width)	C100IV C100IV
Porcelain Enamel	—	—	5500 to 6500 28 to 33	35 10	Rough: .001 Finish .0005 max. Rough: .025 Finish .013 max.	.020-.100 (Max: 1/12 of Wheel Width) .5-2.5 (Max: 1/12 of Wheel Width)	C54IV C54IV

See section 16 for Cutting Fluid Recommendations.
*Wheel recommendations are for wet grinding. For DRY grinding—use a softer grade wheel. Also see section 20.2, Grinding Guidelines.

§Cubic boron nitride wheel is preferable, see section 8.2.

8.1 Surface Grinding-Horizontal Spindle, Reciprocating Table

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE SPEED fpm m/min	DOWNFEED in/pass mm/pass	CROSSFEED in/pass mm/pass	WHEEL* IDENTIFI-CATION ANSI ISO
55. GLASSES & CERAMICS (cont.)			5000 to 5500	50 to 100	Rough .002 Finish .0005 max.	025-.250 (Max 1/10 of Wheel Width)	Rough: C46IV‡ Finish C60IV‡
Ceramics	Over 800 Knoop	Fired	25 to 28	15 to 30	Rough: .050 Finish .013 max.	.65-6.5 (Max. 1/10 of Wheel Width)	Rough: C46IV‡ Finish C60IV‡
Alumina (Aluminum Oxide) Alumina-Mullite Aluminum Silicate Beryllia (Beryllium Oxide)†† Magnesia (Magnesium Oxide) Mullite Silicon Carbide Silicon Nitride Thoria (Thorium Oxide)†† Titania (Titanium Oxide) Titanium Diboride†† Zircon (Zirconium Silicate) Zirconia (Zirconium Oxide)							
56. PLASTICS			5500 to 6500	40	Rough .005 Finish .0005 max.	.050-.500 (Max. 1/3 of Wheel Width)	C54JV
Thermoplastics	—	Cast, Molded, Extruded, or Filled and Molded	28 to 33	12	Rough: .13 Finish .013 max.	1.25-12.5 (Max. 1/3 of Wheel Width)	C54JV
Thermosetting Plastics	—	Cast, Molded or Laminated	5500 to 6500	40	Rough: .005 Finish .0005 max.	.050-.500 (Max: 1/3 of Wheel Width)	A54GV
			28 to 33	12	Rough: .13 Finish .013 max.	1.25-12.5 (Max. 1/3 of Wheel Width)	A54GV
58. FLAME (THERMAL) SPRAYED MATERIALS			5500 to 6500	35 to 50	Rough: .001 Finish .0005 max.	.010-.030 (Max. 1/12 of Wheel Width)	C80FV§
Sprayed Carbides	—	—	24 to 33	11 to 16	Rough: .025 Finish .013 max.	.25-.75 (Max. 1/12 of Wheel Width)	C80FV§
Chromium Carbide Chromium Carbide-Cobalt Blend Columbium Carbide Tantalum Carbide Titanium Carbide Tungsten Carbide Tungsten Carbide-Cobalt Tungsten Carbide (Cobalt)-Nickel Alloy Blend							
Inorganic Coating Materials			5500 to 6500	35 to 50	Rough: .001 Finish .0005 max.	.010-.030 (Max: 1/12 of Wheel Width)	C100GV§
Alumina (Pure) Alumina (Grey) containing Titania Alumina, Nickel-Aluminide Blends Barium Titanate	—	—	24 to 33	11 to 16	Rough: .025 Finish .013 max.	.25-.75 (Max. 1/12 of Wheel Width)	C100GV§
Boron†† Calcium Titanate Calcium Zirconate Chromium Disilicide†† Chromium Oxide†† Cobalt (40%), Zirconia Blend Columbium (Niobium)†† Glass (Kovar sealing)†† Hexaboron Silicide†† Magnesia Alumina Spinel							

(materials continued on next page)

See section 13 for Cutting Fluid Recommendations.

*Wheel recommendations are for wet grinding. For DRY grinding—use a softer grade wheel. Also see section 20.2, Grinding Guidelines.

‡Diamond wheel is preferable, see section 8.3

§Diamond wheel is preferable for flame sprayed carbides and ceramics, see section 8.3.

††CAUTION. Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions

Surface Grinding-Horizontal Spindle, Reciprocating Table 8.1

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE SPEED fpm m/min	DOWNFEED in/pass mm/pass	CROSSFEED in/pass mm/pass	WHEEL* IDENTIFI-CATION ANSI ISO
58. FLAME (THERMAL) SPRAYED MATERIALS (cont.) **Inorganic Coating Materials (cont.)** (materials continued from preceding page) Magnesium Zirconate Molybdenum Disilicide Mullite Nickel (40%), Alumina Blend Nickel Oxide Rare Earth Oxides Tantalum Titania (50%), Alumina Blend Titanium Oxide Tungsten Yttrium Zirconate Zirconia (Lime Stabilized) Zirconia, Nickel-Aluminide Blends Zirconium Oxide (Hafnia Free, Lime Stabilized) Zirconium Silicate							
Sprayed Metals (Group I) Co-Cr-B Alloy (Self Fluxing) Ni-Cr-B Alloy (Self Fluxing) Nickel Chrome Steel (Special) Stainless Steel	—	—	5500 to 6500 28 to 33	35 to 75 11 to 23	Rough: .001 Finish .0005 max. Rough: .025 Finish .013 max.	.010-.100 (Max: 1/10 of Wheel Width) .25-2.5 (Max: 1/10 of Wheel Width)	C46HV C46HV
Sprayed Metals (Group II) Bronze Chromium Cobalt Nickel Molybdenum Monel	—	—	5500 to 6500 28 to 33	40 to 100 12 to 30	Rough: .001 Finish .0005 max Rough: .025 Finish .013 max.	.015-.120 (Max: 1/10 of Wheel Width) .40-3.0 (Max: 1/10 of Wheel Width)	C60JV C46JV
Sprayed Metals (Group III) Carbon Steel Iron Precipitation Hardening Steel	—	—	5500 to 6500 28 to 33	40 to 100 12 to 30	Rough: .001 Finish .0005 max. Rough: .025 Finish .013 max.	.015-.120 (Max: 1/10 of Wheel Width) .40-3.0 (Max: 1/10 of Wheel Width)	C46JV C46JV
59. PLATED MATERIALS Chromium Plate	—	—	3000 to 4000 16 to 20	30 8	Rough: .001 Finish .0005 max. Rough: .025 Finish .013 max.	.025-.250 (Max: 1/10 of Wheel Width) .65-6.5 (Max: 1/10 of Wheel Width)	A60HV A60HV
Nickel Plate Silver Plate	—	—	5500 to 6500 28 to 33	40 12	Rough: .001 Finish .0005 max. Rough: .025 Finish .013 max.	.040-.400 (Max: 1/6 of Wheel Width) 1.0-10.0 (Max: 1/6 of Wheel Width)	C60HV C60HV

See section 16 for Cutting Fluid Recommendations.
*Wheel recommendations are for wet grinding. For DRY grinding—use a softer grade wheel. Also see section 20.2, Grinding Guidelines

8.1 Surface Grinding-Horizontal Spindle, Reciprocating Table

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE SPEED fpm m/min	DOWNFEED in/pass mm/pass	CROSSFEED in/pass mm/pass	WHEEL* IDENTIFI-CATION ANSI ISO
61. RUBBER	Soft	—	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .003 Finish 001 max. Rough: .075 Finish .025 max.	.050- 500 (Max. 1/4 of Wheel Width) 1.25-12.5 (Max. 1/4 of Wheel Width)	C24NB C24NB
	Hard	—	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .003 Finish 001 max. Rough: .075 Finish .025 max.	050-.500 (Max. 1/4 of Wheel Width) 1.25-12.5 (Max. 1/4 of Wheel Width)	C24LB C24LB

See section 16 for Cutting Fluid Recommendations
*Wheel recommendations are for wet grinding For DRY grinding—use a softer grade wheel Also see section 20.2, Grinding Guidelines.

Surface Grinding-Horizontal Spindle, Reciprocating Table 8.2

Cubic Boron Nitride Wheels

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED DRY fpm	WHEEL SPEED WET* fpm	TABLE SPEED fpm	DOWNFEED in/pass	CROSSFEED in/pass	WHEEL IDENTIFI-CATION ANSI
1. FREE MACHINING CARBON STEELS, WROUGHT **Low Carbon Resulfurized** 1108 1118 1109 1119 1110 1211 1115 1212 1116 1213 1117 1215 **Medium Carbon Resulfurized** 1132 1140 1145 1137 1141 1146 1139 1144 1151 **Low Carbon Leaded** 10L18 12L13 12L15 11L17 12L14 **Medium Carbon Leaded** 10L45 11L37 11L44 10L50 11L41	Over 50 R_C	Carburized and/or Quenched and Tempered	4000	5500 to 8000	50 to 125	Rough: 001—.002 Finish. 0005 max.	.25—1.00 (Max· 1/2 of Wheel Width)	B100T75B
2. CARBON STEELS, WROUGHT **Low Carbon** 1005 1012 1019 1026 1006 1013 1020 1029 1008 1015 1021 1513 1009 1016 1022 1518 1010 1017 1023 1522 1011 1018 1025 **Medium Carbon** 1030 1042 1053 1541 1033 1043 1055 1547 1035 1044 1524 1548 1037 1045 1525 1551 1038 1046 1526 1552 1039 1049 1527 1040 1050 1536 **High Carbon** 1060 1074 1085 1566 1064 1075 1086 1572 1065 1078 1090 1069 1080 1095 1070 1084 1561	Over 50 R_C	Carburized and/or Quenched and Tempered	4000	5500 to 8000	50 to 125	Rough: .001—.002 Finish: .0005 max.	.25—1.00 (Max: 1/2 of Wheel Width)	B100T75B

*See section 16 for Cutting Fluid Recommendations.
See section 20 for additional information.

8.2 Surface Grinding-Horizontal Spindle, Reciprocating Table

Cubic Boron Nitride Wheels

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED DRY fpm m/s	WHEEL SPEED WET* fpm m/s	TABLE SPEED fpm m/min	DOWNFEED in/pass mm/pass	CROSSFEED in/pass mm/pass	WHEEL IDENTIFI-CATION ANSI
4. FREE MACHINING ALLOY STEELS, WROUGHT **Medium Carbon Resulfurized** 4140 4140Se 4142Te 4145Se 4147Te 4150 **Medium and High Carbon Leaded** 41L30 41L47 51L32 86L40 41L40 41L50 52L100 41L45 43L40 86L20	Over 50 R_C	Carburized and/or Quenched and Tempered	4000 20	5500 to 8000 28 to 41	50 to 125 15 to 38	Rough: .001—.002 Finish: 0005 max. Rough: .025—.050 Finish: .013 max.	.25—1.00 (Max: 1/2 of Wheel Width) 6.3—25 (Max: 1/2 of Wheel Width)	B100T75B B100T75B
5. ALLOY STEELS, WROUGHT **Low Carbon** 4012 4615 4817 8617 4023 4617 4820 8620 4024 4620 5015 8622 4118 4621 5115 8822 4320 4718 5120 9310 4419 4720 6118 94B15 4422 4815 8115 94B17 **Medium Carbon** 1330 4145 5132 8640 1335 4147 5135 8642 1340 4150 5140 8645 1345 4161 5145 86B45 4027 4340 5147 8650 4028 4427 5150 8655 4032 4626 5155 8660 4037 50B40 5160 8740 4042 50B44 51B60 8742 4047 5046 6150 9254 4130 50B46 81B45 9255 4135 50B50 8625 9260 4137 5060 8627 94B30 4140 50B60 8630 4142 5130 8637 **High Carbon** 50100 51100 52100 M-50	Over 50 R_C	Carburized and/or Quenched and Tempered	4000 20	5500 to 8000 28 to 41	50 to 125 15 to 38	Rough: .001—.002 Finish: .0005 max Rough: .025—.050 Finish: .013 max.	.25—1.00 (Max: 1/2 of Wheel Width) 6.3—25 (Max: 1/2 of Wheel Width)	B100T75B B100T75B

*See section 16 for Cutting Fluid Recommendations
See section 20 for additional information.

Surface Grinding-Horizontal Spindle, Reciprocating Table 8.2

Cubic Boron Nitride Wheels

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED DRY fpm m/s	WHEEL SPEED WET* fpm m/s	TABLE SPEED fpm m/min	DOWNFEED in/pass mm/pass	CROSSFEED in/pass mm/pass	WHEEL IDENTIFI-CATION ANSI ANSI
6. HIGH STRENGTH STEELS, WROUGHT 300M H11 4330V H13 4340 HP 9-4-20 4340Si HP 9-4-25 98BV40 HP 9-4-30 D6ac HP 9-4-45	Over 50 R_C	Quenched and Tempered	4000 20	5500 to 8000 28 to 41	50 to 125 15 to 38	Rough: .001—.002 Finish: .0005 max Rough: .025—.050 Finish: .013 max.	.25—1.00 (Max 1/2 of Wheel Width) 6.3—25 (Max. 1/2 of Wheel Width)	B100T75B B100T75B
7. MARAGING STEELS, WROUGHT 120 Grade 300 Grade 180 Grade 350 Grade 200 Grade HY230 250 Grade ASTM A538: Grades A, B, C	Over 50 R_C	Maraged	4000 20	5500 to 8000 28 to 41	50 to 125 15 to 38	Rough: .001— 002 Finish: .0005 max. Rough: .025—.050 Finish: .013 max.	.25—1.00 (Max: 1/2 of Wheel Width) 6.3—25 (Max. 1/2 of Wheel Width)	B100T75B B100T75B
8. TOOL STEELS, WROUGHT **Group I** A2 H13 L6 P20 A3 H14 L7 P21 A4 H19 O1 S1 A6 H21 O2 S2 A8 H22 O6 S5 A9 H23 O7 S6 A10 H24 P2 S7 H10 H25 P4 W1 H11 H26 P5 W2 H12 L2 P6 W5 SAE J438b. Types W108, W109, W110, W112, W209, W210, W310	Over 50 R_C	Quenched and Tempered	4000 20	5500 to 8000 28 to 41	50 to 125 15 to 38	Rough: .0005—.0015 Finish: .0005 max. Rough: .025—.050 Finish: .013 max.	.12—1.00 (Max: 1/2 of Wheel Width) 3.2—25 (Max. 1/2 of Wheel Width)	B100T75B B100T75B

*See section 16 for Cutting Fluid Recommendations.
See section 20 for additional information

8.2 Surface Grinding-Horizontal Spindle, Reciprocating Table

Cubic Boron Nitride Wheels

MATERIAL	HARDNESS Bhn	CONDITION	WHEEL SPEED DRY fpm / m/s	WHEEL SPEED WET* fpm / m/s	TABLE SPEED fpm / m/min	DOWNFEED in/pass / mm/pass	CROSSFEED in/pass / mm/pass	WHEEL IDENTIFICATION ANSI / ANSI
8. TOOL STEELS, WROUGHT (cont.) **Group II** D2 H42 M42 D3 M1 T1 D4 M2 T2 D5 M3-1 T4 F1 M10 T8 F2 M30	Over 50 R_C	Quenched and Tempered	4000	5500 to 8000	50 to 125	Rough: 0005—.0015 Finish: .0005 max.	.12—1.00 (Max: 1/2 of Wheel Width)	B100T75B
			20	28 to 41	15 to 38	Rough: .013—.038 Finish: .013 max.	3.0—25 (Max: 1/2 of Wheel Width)	B100T75B
Group III A7 M41 D7 M43 M3-2 M44 M6 M46 M7 M47 M33 T5 M34 T6 M36	Over 50 R_C	Quenched and Tempered	4000	5500 to 8000	50 to 125	Rough: .0005—.0015 Finish: .0005 max.	.12—1.00 (Max: 1/2 of Wheel Width)	B100T75B
			20	28 to 41	15 to 38	Rough: .013—.038 Finish: .013 max.	3.0—25 (Max: 1/2 of Wheel Width)	B100T75B
Group IV M4 T15	Over 50 R_C	Quenched and Tempered	4000	5500 to 8000	50 to 125	Rough: .0005—.0010 Finish: .0002 max.	.06—1.00 (Max: 1/2 of Wheel Width)	B100T75B
			[illegible]	28 to 41	15 to 38	Rough: .013—.038 Finish: .013 max.	1.5—25 (Max: 1/2 of Wheel Width)	[illegible]
9. NITRIDING STEELS, WROUGHT Nitralloy 125 Nitralloy 135 Nitralloy 135 Mod. Nitralloy 225 Nitralloy 230 Nitralloy EZ Nitralloy N Nitrex 1	60 R_C to 65 R_C	Nitrided	4000	5500 to 8000	50 to 125	Rough: .001—.002 Finish: .0005 max.	.25—1.00 (Max: 1/2 of Wheel Width)	B100T75B
			[illegible]	28 to 41	15 to 38	[illegible]	[illegible]	[illegible]

*See section 16 for Cutting Fluid Recommendations.
See section 20 for additional information.

Surface Grinding-Horizontal Spindle, Reciprocating Table 8.2

Cubic Boron Nitride Wheels

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED DRY fpm m/s	WHEEL SPEED WET* fpm m/s	TABLE SPEED fpm m/min	DOWNFEED in/pass mm/pass	CROSSFEED in/pass mm/pass	WHEEL IDENTIFI-CATION ANSI
13. STAINLESS STEELS, WROUGHT **Martensitic** 403 440A 410 440B 414 440C 420 501 422 502 431 Greek Ascoloy	Over 45 R_c	Quenched and Tempered	4000	5500 to 8000	50 to 125	Rough: .001—.002 Finish: .0005 max	.25—1.00 (Max: 1/2 of Wheel Width)	B100T75B
			20	28 to 41	15 to 38	Rough: .025—.050 Finish: .013 max	6.3—25 (Max: 1/2 of Wheel Width)	B100T75B
15. CARBON STEELS, CAST **Low Carbon** ASTM A426: Grade CP1 1010 1020 **Medium Carbon** ASTM A352: Grades LCA, LCB, LCC ASTM A356: Grade 1 1030 1040 1050	Over 50 R_c	Carburized and/or Quenched and Tempered	4000	5500 to 8000	50 to 125	Rough: .001—.002 Finish: .0005 max	.25—1.00 (Max: 1/2 of Wheel Width)	B100T75B
			20	28 to 41	15 to 38	Rough: .025—.050 Finish: .013 max	6.3—25 (Max: 1/2 of Wheel Width)	B100T75B
16. ALLOY STEELS, CAST **Low Carbon** ASTM A217: Grade WC9 ASTM A352: Grades LC3, LC4 ASTM A426: Grades CP2, CP5, CP5b, CP11, CP12, CP15, CP21, CP22 1320 2320 4120 8020 2315 4110 4320 8620 **Medium Carbon** ASTM A27: Grades N1, N2, U-60-30, 60-30, 65-35, 70-36, 70-40 ASTM A148: Grades 80-40, 80-50, 90-60, 105-85, 120-95, 150-125, 175-145 ASTM A216: Grades WCA, WCB, WCC ASTM A217: Grades WC1, WC4, WC5, WC6 ASTM A352: Grades LC1, LC2, LC2-1 ASTM A356: Grades 2, 5, 6, 8, 9, 10 ASTM A389: Grades C23, C24 ASTM A486: Classes 70, 90, 120 (materials continued on next page)	Over 50 R_c	Carburized and/or Quenched and Tempered	4000	5500 to 8000	50 to 125	Rough: .001—.002 Finish: .0005 max.	.25—1.00 (Max: 1/2 of Wheel Width)	B100T75B
			20	28 to 41	15 to 38	Rough: .025—.050 Finish: .013 max	6.3—25 (Max: 1/2 of Wheel Width)	B100T75B

*See section 16 for Cutting Fluid Recommendations
See section 20 for additional information

8.2 Surface Grinding-Horizontal Spindle, Reciprocating Table

Cubic Boron Nitride Wheels

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED DRY fpm m/s	WHEEL SPEED WET* fpm m/s	TABLE SPEED fpm m/min	DOWNFEED in/pass mm/pass	CROSSFEED in/pass mm/pass	WHEEL IDENTIFI-CATION ANSI ANSI
16. ALLOY STEELS, CAST (cont.) **Medium Carbon (cont.)** (materials continued from preceding page) ASTM A487: Classes 1N, 2N, 4N, 6N, 8N, 9N, 10N, DN, 1Q, 2Q, 4Q, 4QA, 6Q, 7Q, 8Q 9Q, 10Q 1330 4130 80B30 8640 1340 4140 8040 9525 2325 4330 8430 9530 2330 4340 8440 9535 4125 8030 8630								
17. TOOL STEELS, CAST ASTM A597: Grades CA-2, CD-2, CD-5, CH-12, CH-13, CO-1, CS-5	Over 50 R_C	Quenched and Tempered	4000	5500 to 8000	50 to 125	Rough: .001—.002 Finish: .0005 max.	.25—1.00 (Max: 1/2 of Wheel Width)	B100T75B
21. GRAY CAST IRONS **Ferritic** ASTM A48: Class 20 SAE J431c: Grade G1800 **Pearlitic- Ferritic** ASTM A48: Class 25 SAE J431c: Grade G2500 **Pearlitic** ASTM A48: Classes 30, 35, 40 SAE J431c: Grade G3000 **Pearlitic + Free Carbides** ASTM A48: Classes 45, 50 SAE J431c: Grades G3500, G4000 **Pearlitic or Acicular + Free Carbides** ASTM A48: Classes 55, 60	45 R_C to 60 R_C	As Cast, Annealed, Quenched and Tempered or Flame or Induction Hardened	4000	5500 to 8000	50 to 125	Rough: .001—.002 Finish: .0005 max.	.25—1.00 (Max: 1/2 of Wheel Width)	B100T75B

*See section 16 for Cutting Fluid Recommendations
See section 20 for additional information.

Surface Grinding-Horizontal Spindle, Reciprocating Table 8.2

Cubic Boron Nitride Wheels

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED DRY fpm m/s	WHEEL SPEED WET* fpm m/s	TABLE SPEED fpm m/min	DOWNFEED in/pass mm/pass	CROSSFEED in/pass mm/pass	WHEEL IDENTIFI-CATION ANSI ANSI
23. DUCTILE CAST IRONS **Ferritic** ASTM A536: Grades 60-40-18, 65-45-12 SAE J434c: Grades D4018, D4512 **Ferritic- Pearlitic** ASTM A536, Grade 80-55-06 SAE J434c, Grade D5506 **Pearlitic- Martensitic** ASTM A536 Grade 100-70-03 SAE J434c Grade D7003 **Martensitic** ASTM A536 Grade 120-90-02 SAE J434c, Grade DQ&T	Over 52 R_C	Flame or Induction Hardened	4000 20	5500 to 8000 28 to 41	50 to 125 15 to 38	Rough: 001— 002 Finish 0005 max. Rough: .025—.050 Finish: .013 max.	.25—1 00 (Max 1/2 of Wheel Width) 6.3—25 (Max: 1/2 of Wheel Width)	B100T75B B100T75B
24. MALLEABLE CAST IRONS **Ferritic** ASTM A47: Grades 32510, 35018 ASTM A602: Grade M3210 SAE J158: Grade M3210 **Pearlitic** ASTM A220, Grades 40010, 45006, 45008, 50005 ASTM A602: Grade M4504, M5003 SAE J158: Grades M4504, M5003 **Tempered Martensite** ASTM A220: Grades 60004, 70003, 80002, 90001 ASTM A602 Grades M5503, M7002, M8501 SAE J158 Grades M5503, M7002, M8501	Over 52 R_C	Flame or Induction Hardened	4000 20	5500 to 8500 28 to 41	50 to 125 15 to 38	Rough .001— 002 Finish, .0005 max. Rough: .025—.050 Finish: .013 max.	.25—1.00 (Max. 1/2 of Wheel Width) 6.3—25 (Max: 1/2 of Wheel Width)	B100T75B B100T75B
25. WHITE CAST IRONS (ABRASION RESISTANT) ASTM A532. Class I, Types A, B, C, D Class II, Types A, B, C, D, E Class III, Type A	Over 45 R_C	As Cast, Annealed or Hardened	4000 20	5500 to 8000 25 to 41	50 to 125 15 to 38	Rough: 0005—.0010 Finish: .0002 max. Rough: .013—.025 Finish: .005 max.	.06—1.00 (Max: 1/2 of Wheel Width) 1.5—25 (Max: 1/2 of Wheel Width)	B100T75B B100T75B

*See section 16 for Cutting Fluid Recommendations
See section 20 for additional information

8.2 Surface Grinding-Horizontal Spindle, Reciprocating Table

Cubic Boron Nitride Wheels

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED DRY fpm m/s	WHEEL SPEED WET* fpm m/s	TABLE SPEED fpm m/min	DOWNFEED in/pass mm/pass	CROSSFEED in/pass mm/pass	WHEEL IDENTIFI-CATION ANSI ANSI
39. HIGH TEMPERATURE ALLOYS, WROUGHT AND CAST								
Nickel Base, Wrought	300 to 475	Solution Treated or Solution Treated and Aged	See Note†	5500 to 8000	50 to 125	Rough .001—.002 Finish 0005 max	25—1 00 (Max: 1/2 of Wheel Width)	B100T75B
AF2-1DA			See Note†	28 to 41	15 to 38	Rough: .025—.050 Finish: .013 max.	6.3—25 (Max: 1/2 of Wheel Width)	B100T75B
Astroloy								
Haynes Alloy 263								
IN-102								
Incoloy Alloy 901								
Incoloy Alloy 903								
Inconel Alloy 617								
Inconel Alloy 625								
Inconel Alloy 700								
Inconel Alloy 702								
Inconel Alloy 706								
Inconel Alloy 718								
Inconel Alloy 721								
Inconel Alloy 722								
Inconel Alloy X-750								
Inconel Alloy 751								
M252								
Nimonic 75								
Nimonic 80								
Nimonic 90								
Nimonic 95								
Rene 41								
Rene 63								
Rene 77								
Rene 95								
Udimet 500								
Udimet 700								
Udimet 710								
Unitemp 1753								
Waspaloy								
Nickel Base, Wrought	240 to 310	Cold Drawn or Aged	See Note†	5500 to 8000	50 to 125	Rough: .001—.002 Finish: .0005 max.	.25—1.00 (Max: 1/2 of Wheel Width)	B100T75B
Hastelloy Alloy B			See Note†	28 to 41	15 to 38	Rough: .025—.050 Finish: .013 max.	6.3—25 (Max: 1/2 of Wheel Width)	B100T75B
Hastelloy Alloy B-2								
Hastelloy Alloy C								
Hastelloy Alloy C-276								
Hastelloy Alloy G								
Hastelloy Alloy S								
Hastelloy Alloy X								
Incoloy Alloy 804								
Incoloy Alloy 825								
Inconel Alloy 600								
Inconel Alloy 601								
Refractaloy 26								
Udimet 630								

*See section 16 for Cutting Fluid Recommendations
See section 20 for additional information

†Not recommended.

Surface Grinding-Horizontal Spindle, Reciprocating Table 8.2

Cubic Boron Nitride Wheels

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED DRY fpm m/s	WHEEL SPEED WET* fpm m/s	TABLE SPEED fpm m/min	DOWNFEED in/pass mm/pass	CROSSFEED in/pass mm/pass	WHEEL IDENTIFI-CATION ANSI ANSI
Nickel Base, Cast B-1900 MAR-M200 GMR-235 MAR-M246 GMR-235D MAR-M421 Hastelloy Alloy B MAR-M432 Hastelloy Alloy C Rene 80 Hastelloy Alloy D Rene 125 IN-100 (Rene 100) SEL IN-738 SEL 15 IN-792 TRW VI A Inconel Alloy 713C Udimet 500 Inconel Alloy 718 Udimet 700 M252 ASTM A296, Grades CW-12M, N-12M, CY-40 ASTM A297: Grades HW, HX ASTM A494: Grades N-12M-1, N-12M-2, CY-40, CW-12M-1, CW-12M-2 ASTM A608: Grades HW50, HX50	200 to 425	As Cast or Cast and Aged	See Note†	5500 to 8000	50 to 125	Rough: 001—.002 Finish: 0005 max	25—1.00 (Max: 1/2 of Wheel Width)	B100T75B
			See Note†	28 to 41	15 to 38	Rough: 0.25—.050 Finish: .013 max.	6.3—25 (Max: 1/2 of Wheel Width)	B100T75B
Cobalt Base, Wrought AiResist 213 Haynes Alloy 25 (L605) Haynes Alloy 188 J-1570 MAR-M905 MAR-M918 S-816 V-36	270 to 320	Solution Treated and Aged	See Note†	5500 to 8000	50 to 125	Rough: 001—.002 Finish: 0005 max.	.25—1.00 (Max: 1/2 of Wheel Width)	B100T75B
			See Note†	28 to 41	15 to 38	Rough: 025—.050 Finish: .013 max.	6.3—25 (Max: 1/2 of Wheel Width)	B100T75B

*See section 16 for Cutting Fluid Recommendations
See section 20 for additional information.

†Not Recommended.

8.2 Surface Grinding-Horizontal Spindle, Reciprocating Table

Cubic Boron Nitride Wheels

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED DRY fpm m/s	WHEEL SPEED WET* fpm m/s	TABLE SPEED fpm m/min	DOWNFEED in/pass mm/pass	CROSSFEED in/pass mm/pass	WHEEL IDENTIFI-CATION ANSI ANSI
39. HIGH TEMPERATURE ALLOYS, WROUGHT AND CAST (cont.) **Cobalt Base, Cast** AiResist 13 MAR-M302 AiResist 215 MAR-M322 FSX-414 MAR-M509 HS-6 NASA Co-W-Re HS-21 WI-52 HS-31 (X-40) X-45 HOWMET #3	290 to 425	As Cast or Cast and Aged	See Note†	5500 to 8000	50 to 125	Rough: 001—002 Finish: 5 max.	.25—1.00 (Max: 1/2 of Wheel Width)	B100T75B
			See Note†	28 to 41	15 to 38	Rough: .025—.050 Finish: .013 max.	6.3—25 (Max: 1/2 of Wheel Width)	B100T75B
51. MAGNETIC ALLOYS Alnico I Alnico V-7 Alnico II Alnico XII Alnico III Columax-5 Alnico IV Hyflux Alnico V-7 Alnico V	45 R_C to 58 R_C	As Cast	—	5500 to 8000	50 to 125	Rough: .010 Finish: 002 max.	.020 (Max: 1/4 of Wheel Width)	B100T75B
			—	28 to 41	15 to 38	Rough: .25 Finish: .050 max.	.50 (Max: 1/4 of Wheel Width)	B100T75B

*See section 16 for Cutting Fluid Recommendations
See section 20 for additional information

†Not recommended.

Surface Grinding-Horizontal Spindle, Reciprocating Table 8.3

Diamond Wheels

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED DRY fpm m/s	WHEEL SPEED WET* fpm m/s	TABLE SPEED fpm m/min	DOWNFEED in/pass mm/pass	CROSSFEED in/pass mm/pass	WHEEL IDENTIFICATION ANSI ANSI
5. ALLOY STEELS, WROUGHT **High Carbon** 50100 51100 52100 M-50	50 R_C to 65 R_C	Carburized and/or Quenched and Tempered	—	5000 to 6000	40	Rough 003	080	D80-N100-B-1/8†
					50	Finish. 0005 max	(Max 1/4 of Wheel Width)	D100-N100-B-1/8†
			—	25 to 30	12	Rough: .075	2.0	D80-N100-B-1/8†
					15	Finish: .013 max.	(Max. 1/4 of Wheel Width)	D100-N100-B-1/8†
8. TOOL STEELS, WROUGHT **Group II** D2 D5 H42 M3-1 M42 T4 D3 F1 M1 M10 T1 T8 D4 F2 M2 M30 T2 **Group III** A7 M6 M34 M43 M47 D7 M7 M36 M44 T5 M3-2 M33 M41 M46 T6	Over 58 R_C	Quenched and Tempered	—	5000 to 6000	40	Rough. 0015	060	D60-N100-B-1/8†
					50	Finish 0005 max	(Max 1/4 of Wheel Width)	D70-N100-B-1/8†
			—	25 to 30	12	Rough: .038	1.50	D60-N100-B-1/8†
					15	Finish: .013 max.	(Max. 1/4 of Wheel Width)	D70-N100-B-1/8†
Group IV M4 T15	Over 58 R_C	Quenched and Tempered	—	5000 to 6000	30	Rough .0015	050	D80-N100-M-1/8
					40	Finish 0005 max	(Max 1/4 of Wheel Width)	D100-N100-M-1/8
			—	25 to 30	9	Rough: .038	1.25	D80-N100-M-1/8
					12	Finish: .013 max.	(Max. 1/4 of Wheel Width)	D100-N100-M-1/8
13. STAINLESS STEELS, WROUGHT **Austenitic** 201 304L 310S 330 202 305 314 347 301 308 316 348 302 309 316L 384 302B 309S 317 385 304 310 321	135 to 275	Annealed or Cold Drawn	—	5000 to 6000	50	Rough .0015	040	D80-N100-M-1/8†
					60	Finish .0005 max	(Max 1/4 of Wheel Width)	D100-N100-M-1/8†
			—	25 to 30	15	Rough: .038	1.0	D60-N100-M-1/8†
					18	Finish: .013 max.	(Max. 1/4 of Wheel Width)	D100-N100-M-1/8†
21. GRAY CAST IRONS **Ferritic** ASTM A48: Class 20 SAE J431c Grade G1800 **Pearlitic- Ferritic** ASTM A48: Class 25 SAE J431c Grade G2500 **Pearlitic** ASTM A48. Classes 30, 35, 40 SAE J431c: Grade G3000 **Pearlitic + Free Carbides** ASTM A48 Classes 45, 50 SAE J431c. Grades G3500, G4000 **Pearlitic or Acicular + Free Carbides** ASTM A48: Classes 55, 60	48 R_C to 60 R_C	Flame or Induction Hardened	—	5000 to 6000	60	Rough: 002	.060	D80-N100-M-1/8
					65	Finish: 0005 max.	(Max. 1/4 of Wheel Width)	D100-N100-M-1/8
			—	25 to 30	18	Rough: .050	1.50	D80-N100-M-1/8
					20	Finish: .013 max.	(Max. 1/4 of Wheel Width)	D100-N100-M-1/8

*See section 16 for Cutting Fluid Recommendations
See section 20 for additional information

†Metal-coated diamond

8.3 Surface Grinding-Horizontal Spindle, Reciprocating Table

Diamond Wheels

MATERIAL	HARD-NESS Bhn	CONDITION	[illegible] fpm m/s	TABLE SPEED fpm m/min	DOWNFEED in/pass mm/pass	CROSSFEED in/pass mm/pass	WHEEL IDENTIFICATION ANSI ANSI
48. MACHINABLE CARBIDES Ferro-Tic	68 R_C to 72 R_C	Hardened and Tempered	— 1300 to 1500	20	Rough .002	.030	D100-L100-B-1/8
				30	Finish .0005 max.	(Max 1/4 of Wheel Width)	D150-L100-B-1/8
			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
49. CARBIDES Titanium Carbide Tungsten Carbide	89 R_A to 94 R_A	—	— 5000 to 6000	40	Rough: .001	.050	D150-R100-B-1/4
				50	Finish. .0005 max	(Max 1/4 of Wheel Width)	D220-R75-B-1/8
			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	89 R_A to 94 R_A	—	2500 to 3500 —	5	Rough .002	.030	D200-N100-M-1/4
				6	Finish .001 max	(Max 1/4 of Wheel Width)	D240-N75-M-1/8
			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
51. MAGNETIC ALLOYS Magnetic Core Iron (up to 4% Si) Hi Perm 49 HyMu 80	185 to 240	Wrought	— 5000 to 6000	30	Rough. .005	.030	D120-N75-M-1/8
				40	Finish .001 max	(Max. 1/8 of Wheel Width)	D150-N75-M-1/8
			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Alnico I Alnico II Alnico III Alnico IV Alnico V Alnico V-7 Alnico XII Columax-5 Hyflux Alnico V-7	45 R_C to 58 R_C	As Cast	— 2500 to 3500	8	Rough .002	.030	D150-R100-B-1/8
				10	Finish. 0005 max.	(Max 1/8 of Wheel Width)	D220-R75-B-1/8
			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
54. CARBONS & GRAPHITES Mechanical Grades Brush Grade Carbon	8 to 100 Shore	Molded or Extruded	5500 to 6500 —	40	Rough .005	050	D60-N50-M-1/8
				50	Finish 001 max.	(Max. 1/4 of Wheel Width)	D150-N50-M-1/8
			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

*See section 16 for Cutting Fluid Recommendations
See section 20 for additional information

Surface Grinding-Horizontal Spindle, Reciprocating Table 8.3

Diamond Wheels

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED DRY fpm m/s	WHEEL SPEED WET* fpm m/s	TABLE SPEED fpm m/min	DOWNFEED in/pass mm/pass	CROSSFEED in/pass mm/pass	WHEEL IDENTIFICATION ANSI ANSI
Graphite	—	—	5500 to 6500	—	30	Rough 003	050	D60-N50-M-1/8
					40	Finish 001 max	(Max 1/4 of Wheel Width)	D220-N50-M-1/8
			28 to 33	—	9	Rough: .075	1.25	D60-N50-M-1/8
					12	Finish: .025 max.	(Max: 1/4 of Wheel Width)	D220-N50-M-1/8
55. GLASSES & CERAMICS Machinable Glass-Ceramic (MACOR)	250 Knoop 100g	Cast	—	6500 to 7500	6	Rough .010	050	D100-N100-M-1/8
					8	Finish 002 max	(Max 1/6 of Wheel Width)	D220-N100-M-1/8
			—	33 to 38	1.8	Rough: .25	1.25	D100-N100-M-1/8
					2.4	Finish: .050 max.	(Max: 1/6 of Wheel Width)	D220-N100-M-1/8
PYROCERAM	700 Knoop 100g	—	—	5500 to 6500	30	Rough 003	.050	D60-N100-M-1/8
					40	Finish .001 max	(Max 1/8 of Wheel Width)	D220-N100-M-1/8
			—	28 to 33	9	Rough: .075	1.25	D60-N100-M-1/8
					12	Finish: .025 max.	(Max: 1/8 of Wheel Width)	D220-N100-M-1/8
Glass	480 to 530 Knoop 100g	—	—	5500 to 6500	20	Rough 003	.030	D60-N100-M-1/8
					30	Finish. .0005 max	(Max 1/8 of Wheel Width)	D220-N100-M-1/8
			—	28 to 33	6	Rough: .075	.75	D60-N100-M-1/8
					9	Finish: .013 max.	(Max: 1/8 of Wheel Width)	D220-N100-M-1/8
Ceramics Alumina (Aluminum Oxide) Alumina-Mullite Aluminum Silicate Beryllia (Beryllium Oxide)†† Magnesia (Magnesium Oxide) Mullite Silicon Carbide Silicon Nitride Thoria (Thorium Oxide)†† Titania (Titanium Oxide) Titanium Diboride†† Zircon (Zirconium Silicate) Zirconia (Zirconium Oxide)	Over 800 Knoop	Fired	—	4500 to 5500	50	Rough: .002	.080	D120-N100-M-1/8
					60	Finish: .0005 max.	(Max: 1/4 of Wheel Width)	D220-N100-M-1/8
			—	23 to 28	15	Rough: .025	2.00	D120-N100-M-1/8
					18	Finish: .013 max.	(Max: 1/4 of Wheel Width)	D220-N100-M-1/8

*See section 16 for Cutting Fluid Recommendations. See section 20 for additional information

††CAUTION. Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions.

8.3 Surface Grinding-Horizontal Spindle, Reciprocating Table

Diamond Wheels

MATERIAL	HARD-NESS	CONDITION	WHEEL SPEED DRY	WHEEL SPEED WET*	TABLE SPEED	DOWNFEED	CROSSFEED	WHEEL IDENTIFICATION
	Bhn		fpm m/s	fpm m/s	fpm m/min	in/pass mm/pass	in/pass mm/pass	ANSI ANSI
57. COMPOSITES Kevlar 49 Graphite Epoxy Fiberglass Epoxy (E) Glass (S) Glass Boron Epoxy	—	—	5500 to 6500	—	5 6	Rough .003 Finish .001 max	.030 (Max 1/8 of Wheel Width)	D180-R100-M-1/8 D220-N100-M-1/8
			28 to 33		1.5 1.8	Rough: .075 Finish: .025 max.	.75 (Max. 1/8 of Wheel Width)	D180-R100-M-1/8 D220-N100-M-1/8
58. FLAME (THERMAL) SPRAYED MATERIALS **Sprayed Carbides** Chromium Carbide Chromium Carbide-Cobalt Blend Columbium Carbide Tantalum Carbide Titanium Carbide Tungsten Carbide Tungsten Carbide-Cobalt Tungsten Carbide (Cobalt)-Nickel Alloy Blend	—	—	5500 to 6500	5500 to 6500	35 50	Rough: 002 Finish: 0005 max	030 (Max. 1/8 of Wheel Width)	D120-N100-B-1/8 D320-R75-B-1/8
			28 to 33	28 to 33	11 15	Rough: .050 Finish: .013 max.	.75 (Max. 1/8 of Wheel Width)	D120-N100-B-1/8 D320-R75-B-1/8
Inorganic Coating Materials Alumina (Pure) Alumina (Grey) containing Titania Alumina, Nickel-Aluminide Blends Barium Titanate Boron†† Calcium Titanate Calcium Zirconate Chromium Disilicide†† Chromium Oxide†† Cobalt (40%), Zirconia Blend Columbium (Niobium)†† Glass (Kovar sealing)†† Hexaboron Silicide†† Magnesia Alumina Spinel Magnesium Zirconate Molybdenum Disilicide Nickel (40%), Alumina Blend Nickel Oxide Rare Earth Oxides Titania (50%), Alumina Blend Titanium Oxide Yttrium Zirconate Zirconia (Lime Stabilized) Zirconia, Nickel-Aluminide Blends Zirconium Oxide (Hafnia Free, Lime Stabilized) Zirconium Silicate	—	—	5500 to 6500	5500 to 6500	35 50	Rough: .003 Finish: 001 max.	030 (Max: 1/8 of Wheel Width)	D120-N100-M-1/8 D220-N75-M-1/8
Mullite Tantalum Tungsten			28 to 33	28 to 33	11 15	Rough: .075 Finish: .025 max.	.75 (Max. 1/8 of Wheel Width)	D120-N100-M-1/8 D220-N75-M-1/8

*See section 16 for Cutting Fluid Recommendations
See section 20 for additional information.

††CAUTION Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions

Surface Grinding-Vertical Spindle, Rotary Table 8.4

MATERIAL	HARD-NESS	CONDITION	WHEEL SPEED	TABLE* (WORK) SPEED	DOWNFEED per rev. of table	OPERATION	WHEEL IDENTIFICATION	
							NARROW WORK AREA	BROAD WORK AREA
	Bhn		fpm m/s	fpm m/min	in mm		ANSI ISO	ANSI ISO
1. FREE MACHINING CARBON STEELS, WROUGHT **Low Carbon Resulfurized** 1108 1115 1118 1212 1109 1116 1119 1213 1110 1117 1211 1215 **Medium Carbon Resulfurized** 1132 1140 1145 1137 1141 1146 1139 1144 1151 **Low Carbon Leaded** 10L18 12L13 12L15 11L17 12L14 **Medium Carbon Leaded** 10L45 11L37 11L44 10L50 11L41	50 R_C max.	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	3500 to 6000	80 to 200	.001 to 005	Roughing Finishing	A30IV A80IB	A30HV A80HB
			18 to 30	24 to 60	.025 to 13	Roughing Finishing	A30IV A80IB	A30HV A80HB
	Over 50 R_C	Carburized and/or Quenched and Tempered	3500 to 6000	100 to 250	.0005 to .001	Roughing Finishing	A46GV A80GB	A46FV A80FB
			18 to 30	30 to 76	.013 to .025	Roughing Finishing	A46GV A80GB	A46FV A80FB
2. CARBON STEELS, WROUGHT **Low Carbon** 1005 1012 1019 1026 1006 1013 1020 1029 1008 1015 1021 1513 1009 1016 1022 1518 1010 1017 1023 1522 1011 1018 1025 **Medium Carbon** 1030 1042 1053 1541 1033 1043 1055 1547 1035 1044 1524 1548 1037 1045 1525 1551 1038 1046 1526 1552 1039 1049 1527 1040 1050 1536 **High Carbon** 1060 1074 1085 1566 1064 1075 1086 1572 1065 1078 1090 1069 1080 1095 1070 1084 1561	50 R_C max.	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	3500 to 6000	80 to 200	.001 to .005	Roughing Finishing	A30IV A80IB	A30HV A80HB
			18 to 30	24 to 60	.025 to 13	Roughing Finishing	A30IV A80IB	A30HV A80HB
	Over 50 R_C	Carburized and/or Quenched and Tempered	3500 to 6000	100 to 250	.0005 to .001	Roughing Finishing	A46GV A80GB	A46FV A80FB
			18 to 30	30 to 76	.013 to .025	Roughing Finishing	A46GV A80GB	A46FV A80FB
3. CARBON AND FERRITIC ALLOY STEELS (HIGH TEMPERATURE SERVICE) ASTM A369. Grades FPA, FPB, FP1, FP2, FP3b, FP5, FP7, FP9, FP11, FP12, FP21, FP22	150 to 200	As Forged, Annealed or Normalized and Tempered	3500 to 6000	80 to 200	.001 to .005	Roughing Finishing	A30IV A80IB	A30HV A80HB
			18 to 30	24 to 60	.025 to 13	Roughing Finishing	A30IV A80IB	A30HV A80HB

See section 16 for Cutting Fluid Recommendations
*See section 20 4 for calculation of Table rpm and Downfeed in rpm

8.4 Surface Grinding-Vertical Spindle, Rotary Table

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE* (WORK) SPEED fpm m/min	DOWNFEED per rev. of table in mm	OPERATION	WHEEL IDENTIFICATION NARROW WORK AREA ANSI ISO	WHEEL IDENTIFICATION BROAD WORK AREA ANSI ISO
4. FREE MACHINING ALLOY STEELS, WROUGHT **Medium Carbon Resulfurized** 4140 4142Te 4147Te 4140Se 4145Se 4150 **Medium and High Carbon Leaded** 41L30 41L47 51L32 86L40 41L40 41L50 52L100 41L45 43L40 86L20	50 R_C max.	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	3500 to 6000	80 to 200	.001 to .005	Roughing	A30IV	A30HV
						Finishing	A80IB	A80HB
			16 to 30	24 to 60	.025 to .13	Roughing	A30IV	A30HV
						Finishing	A80IB	A80HB
	Over 50 R_C	Carburized and/or Quenched and Tempered	3500 to 6000	100 to 250	0005 to .001	Roughing	A46GV	A46FV
						Finishing	A80GB	A80FB
			16 to 30	30 to 76	.013 to .025	Roughing	A46GV	A46FV
						Finishing	A80GB	A80FB
5. ALLOY STEELS, WROUGHT **Low Carbon** 4012 4615 4817 8617 4023 4617 4820 8620 4024 4620 5015 8622 4118 4621 5115 8822 4320 4718 5120 9310 4419 4720 6118 94B15 4422 4815 8115 94B17 **Medium Carbon** 1330 4145 5132 8640 1335 4147 5135 8642 1340 4150 5140 8645 1345 4161 5145 86B45 4027 4340 5147 8650 4028 4427 5150 8655 4032 4626 5155 8660 4037 50B40 5160 8740 4042 50B44 51B60 8742 4047 5046 6150 9254 4130 50B46 81B45 9255 4135 50B50 8625 9260 4137 5060 8627 94B30 4140 50B60 8630 4142 5130 8637 **High Carbon** 50100 51100 52100 M-50	50 R_C max	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	3500 to 6000	80 to 200	.001 to .005	Roughing	A30IV	A30HV
						Finishing	A80IB	A80HB
			16 to 30	24 to 60	.025 to .13	Roughing	A30IV	A30HV
						Finishing	A80IB	A80HB
	Over 50 R_C	Carburized and/or Quenched and Tempered	3500 to 4500	100 to 250	.0005 to .001	Roughing	A46GV	A46FV
						Finishing	A80GB	A80FB
			16 to 23	30 to 76	.013 to .025	Roughing	A46GV	A46FV
						Finishing	A80GB	A80FB
6. HIGH STRENGTH STEELS, WROUGHT 300M 4330V 4340 4340Si 98BV40 D6ac H11 H13 HP 9-4-20 HP 9-4-25 HP 9-4-30 HP 9-4-45	50 R_C max	Annealed, Normalized or Quenched and Tempered	3500 to 6000	80 to 200	.001 to .003	Roughing	A30HV	A30GV
						Finishing	A80HB	A80GB
			16 to 30	24 to 60	.025 to .076	Roughing	A30IV	A30GV
						Finishing	A80IB	A80GB
	Over 50 R_C	Quenched and Tempered	3500 to 4500	100 to 250	.0005 to .001	Roughing	A46GV	A46FV
						Finishing	A100GB	A100FB
			16 to 28	30 to 76	.013 to .025	Roughing	A46GV	A46FV
						Finishing	A100GB	A100FB

See section 16 for Cutting Fluid Recommendations
*See section 20 4 for calculation of Table rpm and Downfeed in ipm

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm	TABLE* (WORK) SPEED fpm	DOWNFEED per rev. of table in	OPERATION	WHEEL IDENTIFICATION NARROW WORK AREA ANSI / ISO	WHEEL IDENTIFICATION BROAD WORK AREA ANSI / ISO
7. MARAGING STEELS, WROUGHT ASTM A538 Grades A, B, C 120 Grade 180 Grade 200 Grade 250 Grade 300 Grade 350 Grade HY230	50 R_C max.	Annealed or Maraged	3500 to 6000	80 to 200	.001 to .005	Roughing Finishing	A30IV A80IB	A30HV A80HB
	Over 50 R_C	Maraged	3500 to 6000	100 to 250	.0005 to .001	Roughing Finishing	A46GV A80GB	A46FV A80FB
8. TOOL STEELS, WROUGHT **Group I** A2 H13 L6 P20 A3 H14 L7 P21 A4 H19 O1 S1 A6 H21 O2 S2 A8 H22 O6 S5 A9 H23 O7 S6 A10 H24 P2 S7 H10 H25 P4 W1 H11 H26 P5 W2 H12 L2 P6 W5 SAE J438b: Types W108, W109, W110, W112, W209, W210, W310	50 R_C max.	Annealed or Quenched and Tempered	3500 to 6000	80 to 200	.001 to .003	Roughing Finishing	A30IV A80IB	A30HV A80HB
	Over 50 R_C	Quenched and Tempered	3500 to 4500	100 to 250	.0005 to .001	Roughing Finishing	A46HV A100HB	A46GV A100GB
Group II D2 F2 M10 T4 D3 H42 M30 T8 D4 M1 M42 D5 M2 T1 F1 M3-1 T2	50 R_C max.	Annealed or Quenched and Tempered	3500 to 6000	80 to 200	.001 to .003	Roughing Finishing	A30HV A80HB	A30GV A80GB
	50 R_C to 58 R_C	Quenched and Tempered	3500 to 4500	100 to 250	.0005 to .001	Roughing Finishing	A46GV A100GB	A46FV A100FB
	Over 58 R_C	Quenched and Tempered	3500 to 4500	100 to 250	0005 to .001	Roughing Finishing	A46GV A100GB	A46FV A100FB
Group III A7 M7 M41 M47 D7 M33 M43 T5 M3-2 M34 M44 T6 M6 M36 M46	50 R_C max.	Annealed or Quenched and Tempered	3500 to 6000	80 to 200	.001 to .003	Roughing Finishing	A30HV A80HB	A30GV A80GB
	50 R_C to 58 R_C	Quenched and Tempered	3500 to 4500	100 to 250	.0005 to .001	Roughing Finishing	A46GV A100GB	A46FV A100FB

See section 16 for Cutting Fluid Recommendations
*See section 20.4 for calculation of Table rpm and Downfeed in rpm

8.4 Surface Grinding-Vertical Spindle, Rotary Table

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE* (WORK) SPEED fpm m/min	DOWNFEED per rev. of table in mm	OPERATION	WHEEL IDENTIFICATION NARROW WORK AREA ANSI ISO	WHEEL IDENTIFICATION BROAD WORK AREA ANSI ISO
8. TOOL STEELS, WROUGHT (cont.) **Group III (cont.)** (materials listed on preceding page)	Over 58 R_C	Quenched and Tempered	3500 to 4500	100 to 250	0005 to 001	Roughing	A46GV	A46FV
						Finishing	A100GB	A100FB
			18 to 23	30 to 76	.013 to .025	Roughing	A46GV	A46FV
						Finishing	A100GB	A100FB
Group IV M4 T15	50 R_C max	Annealed or Quenched and Tempered	3500 to 6000	80 to 200	.001 to .003	Roughing	A30HV	A30GV
						Finishing	A80HB	A80GB
			18 to 30	24 to 60	.025 to .075	Roughing	A30HV	A30GV
						Finishing	A80HB	A80GB
	50 R_C to 58 R_C	Quenched and Tempered	3500 to 4500	100 to 250	0005 to .001	Roughing	A46GV	A46FV
						Finishing	A100GB	A100FB
			18 to 23	30 to 76	.013 to .025	Roughing	A46GV	A46FV
						Finishing	A100GB	A100FB
	Over 58 R_C	Quenched and Tempered	3500 to 4500	100 to 250	0005 to 001	Roughing	A46GV	A46FV
						Finishing	A100GB	A100FB
			18 to 23	30 to 76	.013 to .025	Roughing	A46GV	A46FV
						Finishing	A100GB	A100FB
9. NITRIDING STEELS, WROUGHT Nitralloy 125 Nitralloy 135 Nitralloy 135 Mod. Nitralloy 225 Nitralloy 230 Nitralloy EZ Nitralloy N Nitrex 1	200 to 350	Annealed, Normalized or Quenched and Tempered	3500 to 6000	80 to 200	.001 to .005	Roughing	A30HV	A30GV
						Finishing	A80HB	A80GB
			18 to 30	24 to 60	.025 to .13	Roughing	A30HV	A30GV
						Finishing	A80HB	A80GB
	60 R_C to 65 R_C	Nitrided	3500 to 4500	100 to 250	.0005 to .001	Roughing	A46GV	A46FV
						Finishing	A100GB	A100FB
			18 to 23	30 to 76	.013 to .025	Roughing	A46GV	A46FV
						Finishing	A100GB	A100FB
10. ARMOR PLATE, SHIP PLATE, AIRCRAFT PLATE, WROUGHT HY80 MIL-S-12560 HY100 MIL-S-16216 HY180	45 R_C max.	Annealed or Quenched and Tempered	3500 to 6000	80 to 200	.001 to .003	Roughing	A30HV	A30GV
						Finishing	A80HB	A80GB
			18 to 30	24 to 60	.025 to .075	Roughing	A30HV	A30GV
						Finishing	A80HB	A80GB
11. STRUCTURAL STEELS, WROUGHT** 30 35 42 45 50 55 60 65 70 75 80 85 90 100 110 135 140 145 150 160 165 185 210	48 R_C max.	Hot Rolled, Normalized, Stress Relieved or Quenched and Tempered	3500 to 6000	80 to 200	.001 to 005	Roughing	A24IV	A24HV
						Finishing	A80IB	A80HB
			18 to 30	24 to 60	.025 to .13	Roughing	A24IV	A24HV
						Finishing	A80IB	A80HB
	Over 48 R_C	Quenched and Tempered	3500 to 6000	100 to 250	.0005 to .001	Roughing	A30IV	A30HV
						Finishing	A80GB	A80FB
			18 to 30	30 to 76	.013 to .025	Roughing	A30IV	A30HV
						Finishing	A80GB	A80FB

See section 16 for Cutting Fluid Recommendations

*See section 20 4 for calculation of Table rpm and Downfeed in ipm

**In this handbook, Structural Steels are designated by yield strength in units of 1000 psi. For example, 50 means a steel with 50,000 psi yield strength. Similarly, 140 means 140,000 psi yield strength. Therefore, in order to select the appropriate block of machining data, it is necessary to know the yield strength or Bhn.

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE* (WORK) SPEED fpm m/min	DOWNFEED per rev. of table in mm	OPERATION	WHEEL IDENTIFICATION NARROW WORK AREA ANSI ISO	WHEEL IDENTIFICATION BROAD WORK AREA ANSI ISO
12. FREE MACHINING STAINLESS STEELS, WROUGHT **Ferritic** 430F 430F Se	135 to 185	Annealed	3500 to 6000	100 to 350	.001 to .003	Roughing	A46IV	A46GV
						Finishing	A80HB	A80GB
			18 to 30	30 to 105	.025 to .075	Roughing	A46IV	A46GV
						Finishing	A80HB	A80GB
Austenitic 203EZ 303Pb 303 303 Plus X 303MA 303Se	135 to 275	Annealed or Cold Drawn	3500 to 6000	100 to 350	.001 to .003	Roughing	CA46IB	CA46GB
						Finishing	CA80IB	CA80GB
			18 to 30	30 to 105	.025 to .075	Roughing	CA46IB	CA46GB
						Finishing	CA80IB	CA80GB
Martensitic 416 420F Se 416 Plus X 440F 416Se 440F Se 420F	135 to 240	Annealed or Cold Drawn	3500 to 6000	100 to 350	.001 to .003	Roughing	A46IV	A46GV
						Finishing	A80HB	A80GB
			18 to 30	30 to 105	.025 to .075	Roughing	A46IV	A46GB
						Finishing	A80HB	A80GB
	over 275	Quenched and Tempered	3500 to 6000	100 to 350	.001 to .003	Roughing	A46GV	A46FV
						Finishing	A80GB	A80FB
			18 to 30	30 to 105	.025 to .075	Roughing	A46GV	A46FV
						Finishing	A80GB	A80FB
13. STAINLESS STEELS, WROUGHT **Ferritic** 405 429 434 442 409 430 436 446	135 to 185	Annealed	3500 to 6000	100 to 350	001 to .003	Roughing	A46IV	A46GV
						Finishing	A80HB	A80GB
			18 to 30	30 to 105	.025 to .075	Roughing	A46IV	A46GV
						Finishing	A80HB	A80GB
Austenitic 201 304L 310S 330 202 305 314 347 301 308 316 348 302 309 316L 384 302B 309S 317 385 304 310 321	135 to 275	Annealed or Cold Drawn	3500 to 6000	100 to 350	001 to .003	Roughing	CA46IB	CA46GB
						Finishing	CA80IB	CA80GB
			18 to 30	30 to 105	.025 to .075	Roughing	CA46IB	CA46GB
						Finishing	CA80IB	CA80GB
Austenitic Nitronic 32 Nitronic 50 Nitronic 33 Nitronic 60 Nitronic 40	210 to 375	Annealed or Cold Drawn	3500 to 6000	100 to 350	.001 to .003	Roughing	CA46IB	CA46GB
						Finishing	CA80IB	CA80GB
			18 to 30	30 to 105	.025 to .075	Roughing	CA46IB	CA46GB
						Finishing	CA80IB	CA80GB
Martensitic 403 422 440C 410 431 501 414 440A 502 420 440B Greek Ascoloy	135 to 275	Annealed	3500 to 6000	100 to 350	.001 to .003	Roughing	A46IV	A46GV
						Finishing	A80HB	A80GB
			18 to 30	30 to 105	.025 to .075	Roughing	A46IV	A46GV
						Finishing	A80HB	A80GB
	Over 275	Quenched and Tempered	3500 to 6000	100 to 350	.001 to .003	Roughing	A46GV	A46FV
						Finishing	A80GB	A80FB
			18 to 30	30 to 105	.025 to .075	Roughing	A46GV	A46FV
						Finishing	A80GB	A80FB

See section 16 for Cutting Fluid Recommendations
*See section 20 4 for calculation of Table rpm and Downfeed in rpm

8.4 Surface Grinding-Vertical Spindle, Rotary Table

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/min	TABLE (WORK) SPEED fpm m/min	DOWNFEED per rev. of table in mm	OPERATION	WHEEL IDENTIFICATION NARROW WORK AREA ANSI ISO	WHEEL IDENTIFICATION BROAD WORK AREA ANSI ISO
14. PRECIPITATION HARDENING STAINLESS STEELS, WROUGHT 15-5 PH 16-6 PH 17-4 PH 17-7 PH 17-14 Cu Mo AF-71 AFC-77 Almar 362 (AM-362) AM-350 AM-355 AM-363 Custom 450 Custom 455 HNM PH 13-8 Mo PH 14-8 Mo PH 15-7 Mo Stainless W	150 to 440	Solution Treated or Hardened	3500 to 6000	100 to 350	.001 to .003	Roughing Finishing	A46IV A80HB	A46GV A80GB
			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
15. CARBON STEELS, CAST **Low Carbon** ASTM A426: Grade CP1 1010 1020 **Medium Carbon** ASTM A352: Grades LCA, LCB, LCC ASTM A356: Grade 1 1030 1040 1050	100 to 300	Annealed, Normalized, Normalized and Tempered, or Quenched and Tempered	3500 to 6000	80 to 200	.001 to .005	Roughing Finishing	A30IV A80IB	A30HV A80HB
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Over 50 R_C	Carburized and/or Quenched and Tempered	3500 to 6000	100 to 250	.0005 to .001	Roughing Finishing	A46GV A80GB	A46FV A80FB
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
16. ALLOY STEELS, CAST **Low Carbon** ASTM A217: Grade WC9 ASTM A352: Grades LC3, LC4 ASTM A426: Grades CP2, CP5, CP5b, CP11, CP12, CP15, CP21, CP22 1320 2320 4120 8020 2315 4110 4320 8620 **Medium Carbon** ASTM A27: Grades N1, N2, U-60-30, 60-30, 65-35, 70-36, 70-40 ASTM A148: Grades 80-40, 80-50, 90-60, 105-85, 120-95, 150-125, 175-145 ASTM A216: Grades WCA, WCB, WCC ASTM A217: Grades WC1, WC4, WC5, WC6 ASTM A352 Grades LC1, LC2, LC2-1 (materials continued on next page)	150 to 400	Annealed, Normalized, Normalized and Tempered, or Quenched and Tempered	3500 to 6000	80 to 200	.001 to .005	Roughing Finishing	A30IV A80IB	A30HV A80HB
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Over 50 R_C	Carburized and/or Quenched and Tempered	3500 to 6000	100 to 250	.0005 to .002	Roughing Finishing	A46GV A80GB	A46FV A80FB
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

See section 16 for Cutting Fluid Recommendations
*See section 20.4 for calculation of Table rpm and Downfeed in rpm

MATERIAL	HARD-NESS Bhn	CONDITION	WHFEL SPEED fpm m/s	TABLE* (WORK) SPEED fpm m/min	DOWNFEED per rev. of table in mm	OPERATION	WHEEL IDENTIFICATION NARROW WORK AREA ANSI ISO	WHEEL IDENTIFICATION BROAD WORK AREA ANSI ISO
16. ALLOY STEELS, CAST (cont.) **Medium Carbon (cont.)** (materials continued from preceding page) ASTM A356: Grades 2 5 6 8, 9, 10 ASTM A389: Grades C23, C24 ASTM A486: Classes 70, 90, 120 ASTM A487: Classes 1N, 2N, 4N, 6N, 8N, 9N, 10N, DN, 1Q, 2Q, 4Q, 4QA, 6Q, 7Q, 8Q, 9Q, 10Q 1330 4130 80B30 8640 1340 4140 8640 9525 2325 4330 8430 9530 2330 4340 8440 9535 4125 8030 8630								
17. TOOL STEELS, CAST **Group I** ASTM A597: Grades CA-2, CH-12, CH-13, CO-1, CS-5	50 R_C max.	Annealed or Quenched and Tempered	3500 to 6000	80 to 200	.001 to .003	Roughing	A30IV	A30HV
						Finishing	A80IB	A80HB
			18 to 30	24 to 60	.025 to .075	Roughing	A30IV	A30HV
						Finishing	A80IB	A80HB
	50 R_C to 58 R_C	Quenched and Tempered	3500 to 4500	100 to 250	0005 to .002	Roughing	A46HV	A46GV
						Finishing	A100HB	A100GB
			18 to 23	30 to 76	.013 to .050	Roughing	A46HV	A46GV
						Finishing	A100HB	A100GB
	Over 58 R_C	Quenched and Tempered	3500 to 4500	100 to 250	0005 to .001	Roughing	A46GV	A46FV
						Finishing	A100GB	A100FB
			18 to 23	30 to 76	.013 to .025	Roughing	A46GV	A46FV
						Finishing	A100GB	A100FB
Group II ASTM A597: Grades CD-2, CD-5	200 to 250	Annealed	3500 to 6000	80 to 200	.001 to .003	Roughing	A30IV	A30HV
						Finishing	A80IB	A80HB
			18 to 30	24 to 60	.025 to .075	Roughing	A30IV	A30HV
						Finishing	A80IB	A80HB
	48 R_C to 56 R_C	Quenched and Tempered	3500 to 4500	100 to 250	.0005 to .002	Roughing	A46HV	A46GV
						Finishing	A100HB	A100GB
			18 to 23	30 to 76	.013 to .050	Roughing	A46HV	A46GV
						Finishing	A100HB	A100GB
	Over 56 R_C	Quenched and Tempered	3500 to 4500	100 to 250	.0005 to .001	Roughing	A46GV	A46FV
						Finishing	A100GB	A100FB
			18 to 23	30 to 76	.013 to .025	Roughing	A46GV	A46FV
						Finishing	A100GB	A100FB

See section 16 for Cutting Fluid Recommendations
*See section 20.4 for calculation of Table rpm and Downfeed in ipm

8.4 Surface Grinding-Vertical Spindle, Rotary Table

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE* (WORK) SPEED fpm m/min	DOWNFEED per rev. of table in mm	OPERATION	WHEEL IDENTIFICATION NARROW WORK AREA ANSI ISO	WHEEL IDENTIFICATION BROAD WORK AREA ANSI ISO
18. STAINLESS STEELS, CAST								
Ferritic			3500 to 6000	100 to 350	.001 to .003	Roughing Finishing	A30IV A80IB	A30HV A80HB
ASTM A217 Grades C5, C12	135 to 185	Annealed	18 to 30	30 to 105	.025 to .075	Roughing Finishing	A30IV A80IB	A30HV A80HB
ASTM A296: Grades CB-30, CC-50, CE-30, CA6N, CA-6NM, CD4MCu								
ASTM A297 Grade HC								
ASTM A487 Class CA6NM								
ASTM A608. Grade HC30								
Austenitic			3500 to 6000	100 to 350	.001 to .003	Roughing Finishing	A30IV A80IB	A30HV A80HB
ASTM A296 Grades CF-3, CF-3M, CF-8, CF-8C, CF-8M, CF-16F, CF-20, CG-8M CG-12, CH-20, CK-20, CN-7M, CN-7MS	135 to 210	Annealed, Normalized or As Cast	18 to 30	30 to 105	.025 to .075	Roughing Finishing	A30IV A80IB	A30HV A80HB
ASTM A297 Grades HD, HE, HF, HH, HI, HK, HL, HN, HP, HT, HU								
ASTM A351: Grades CF-3, CF-3A, CF-3M, CF-3MA, CF-8, CF-8A, CF-8C, CF-8M, CF-10MC, CH-8, CH-10, CH-20, CK-20, CN-7M, HK-30 HK-40, HT-30								
ASTM A451: Grades CPF8A, CPF3, CPF3A, CPF3M, CPF8, CPF8C CPF8C (Ta Max.), CPF8M, CPF10MC, CPH8, CPH10, CPH20, CPK20								
ASTM A452. Grades TP 304H, TP 316H, TP 347H								
ASTM A608: Grades HD50, HE35, HF30, HH30, HH33, HI35, HK30, HK40, HL30, HL40, HN40, HT50, HU50								
Martensitic			3500 to 6000	100 to 350	.001 to .003	Roughing Finishing	A30IV A80IB	A30HV A80HB
ASTM A217: Grade CA-15	135 to 225	Annealed Normalized or Normalized and Tempered	18 to 30	30 to 105	.025 to .075	Roughing Finishing	A30IV A80IB	A30HV A80HB
ASTM A296: Grades CA-15, CA-15M, CA-40								
ASTM A426: Grades CP7, CP9, CPCA15								
ASTM A487: Classes CA15a, CA 15M			3500 to 6000	100 to 350	.0005 to .002	Roughing Finishing	A46GV A80GB	A46FV A80FB
	Over 275	Quenched and Tempered	18 to 30	30 to 105	.013 to .050	Roughing Finishing	A46GV A80GB	A46FV A80FB

See section 16 for Cutting Fluid Recommendations.
*See section 20.4 for calculation of Table rpm and Downfeed in rpm

Surface Grinding-Vertical Spindle, Rotary Table 8.4

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE* (WORK) SPEED fpm m/min	DOWNFEED per rev. of table in mm	OPERATION	WHEEL IDENTIFICATION NARROW WORK AREA ANSI ISO	WHEEL IDENTIFICATION BROAD WORK AREA ANSI ISO
19. PRECIPITATION HARDENING STAINLESS STEELS, CAST ASTM A351: Grade CD-4MCu ACI Grade CB-7Cu ACI Grade CD-4MCu 17-4 PH AM-355	325 to 450	Solution Treated or Solution Treated and Aged	3500 to 6000 18 to 30	80 to 200 24 to 60	001 to .003 .025 to .075	Roughing Finishing Roughing Finishing	A30IV A80IB A30IV A80IB	A30HV A80HB A30HV A80HB
21. GRAY CAST IRONS **Ferritic** ASTM A48. Class 20 SAE J431c: Grade G1800 **Pearlitic- Ferritic** ASTM A48: Class 25 SAE J431c: Grade G2500 **Pearlitic** ASTM A48. Classes 30, 35, 40 SAE J431c: Grade G3000 **Pearlitic + Free Carbides** ASTM A48 Classes 45, 50 SAE J431c Grades G3500, G4000 **Pearlitic or Acicular + Free Carbides** ASTM A48: Classes 55, 60	52 R_C max.	As Cast: Annealed or Quenched and Tempered	3500 to 6000 18 to 30	100 to 350 30 to 105	003 to .008 .075 to .20	Roughing Finishing Roughing Finishing	A30IV C80IB A30IV C80IB	A30HV C80HB A30HV C80HB
Austenitic (NI-RESIST) ASTM A436: Types 1, 1b, 2, 2b, 3, 4, 5, 6	100 to 250	As Cast	3500 to 6000 18 to 30	100 to 350 30 to 105	001 to .005 .065 to .13	Roughing Finishing Roughing Finishing	A30HV C80HB A30IV C80IB	A30GV C80GB A30GV C80GB
22. COMPACTED GRAPHITE CAST IRONS	185 to 225	As Cast	3500 to 6000 18 to 30	100 to 350 30 to 105	.001 to .005 .025 to .13	Roughing Finishing Roughing Finishing	A30IV C80IB A30IV C80IB	A30HV C80HB A30HV C80HB
23. DUCTILE CAST IRONS **Ferritic** ASTM A536 Grades 60-40-18, 65-45-12 SAE J434c: Grades D4018, D4512 **Ferritic- Pearlitic** ASTM A536: Grade 80-55-06 SAE J434c: Grade D5506 **Pearlitic- Martensitic** ASTM A536: Grade 100-70-03 SAE J434c: Grade D7003 **Martensitic** ASTM A536: Grade 120-90-02 SAE J434c: Grade DQ&T	52 R_C max.	Annealed, As Cast, Normalized and Tempered or Quenched and Tempered	3500 to 6000 18 to 30	100 to 350 30 to 105	001 to .005 .025 to .13	Roughing Finishing Roughing Finishing	A24HV A80HB A24GV A80HB	A24GV A80GB A24GV A80GB

See section 16 for Cutting Fluid Recommendations.
*See section 20.4 for calculation of Table rpm and Downfeed in ipm.

8.4 Surface Grinding-Vertical Spindle, Rotary Table

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/min	TABLE* (WORK) SPEED fpm m/min	DOWNFEED per rev. of table in mm	OPERATION	WHEEL IDENTIFICATION NARROW WORK AREA ANSI ISO	WHEEL IDENTIFICATION BROAD WORK AREA ANSI ISO
23. DUCTILE CAST IRONS (cont.) **Austenitic (NI-RESIST Ductile)** ASTM A439 Types D-2, D-2B, D-2C, D-3, D-3A, D-4, D-5, D-5B ASTM A571 Type D-2M	120 to 275	Annealed	3500 to 6000 1065 to 1830	100 to 350 30 to 105	.001 to .005 .025 to .13	Roughing Finishing	A30HV A80HB	A30GV A80GB
24. MALLEABLE CAST IRONS **Ferritic** ASTM A47 Grades 32510, 35018 ASTM A602, Grade M3210 SAE J158 Grade M3210 **Pearlitic** ASTM A220 Grades 40010, 45006, 45008, 50005 ASTM A602, Grade M4504, M5003 SAE J158 Grades M4504, M5003 **Tempered Martensite** ASTM A220 Grades 60004, 70003, 80002, 90001 ASTM A602: Grades M5503, M7002, M8501 SAE J158 Grades M5503, M7002, M8501	52 R_C max	Malleablized or Malleablized and Heat Treated	3500 to 6000 1065 to 1830	100 to 350 30 to 105	.001 to .005 .025 to .13	Roughing Finishing	A30HV A80HB	A30GV A80GB
25. WHITE CAST IRONS (ABRASION RESISTANT) ASTM A532: Class I, Types A, B, C, D Class II, Types A, B, C, D, E Class III, Type A	60 R_C max	As Cast, Annealed or Hardened	3500 to 6000 1065 to 1830	100 to 350 30 to 105	.001 to .005 .025 to .13	Roughing Finishing	C24HV C80HB	C24GV C80GB
28. ALUMINUM ALLOYS, WROUGHT EC 2218 5252 6253 1060 2219 5254 6262 1100 2618 5454 6463 1145 3003 5456 6951 1175 3004 5457 7001 1235 3005 5652 7004 2011 4032 5657 7005 2014 5005 6053 7039 (materials continued on next page)	30 to 150 500kg	Cold Drawn or Solution Treated and Aged	3500 to 6000 1065 to 1830	100 to 250 30 to 75	.001 to .004 .025 to .100	Roughing Finishing	CA46IB CA60IB	CA46GB CA60GB

See section 16 for Cutting Fluid Recommendations
*See section 20.4 for calculation of Table rpm and Downfeed in rpm

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE* (WORK) SPEED fpm m/min	DOWNFEED per rev. of table in mm	OPERATION	WHEEL IDENTIFICATION NARROW WORK AREA ANSI ISO	WHEEL IDENTIFICATION BROAD WORK AREA ANSI ISO
28. ALUMINUM ALLOYS, WROUGHT (cont.) (materials continued from preceding page) 2017 5050 6061 7049 2018 5052 6063 7050 2021 5056 6066 7075 2024 5083 6070 7079 2025 5086 6101 7175 2117 5154 6151 7178								
29. ALUMINUM ALLOYS, CAST **Sand and Permanent Mold** A140 295.0 514.0 A712.0 201 0 B295.0 A514.0 D712.0 208.0 308.0 B514.0 713.0 213 0 319 0 520 0 771 0 222.0 355 0 535 0 850 0 224 0 C355 0 705 0 A850 0 242 0 B443.0 707 0 B850.0 Hiduminium RR-350 **Die Castings** C443.0 518 0	40 to 125 500kg	As Cast or Solution Treated and Aged	3500 to 6000	100 to 250	.001 to .004	Roughing Finishing	CA46IB CA60IB	CA46GB CA60GB
			15 to 30	30 to 76	.025 to .100	Roughing Finishing	CA46IB CA60IB	CA46GB CA60GB
Sand and Permanent Mold 328 0 333.0 A356.0 A332.0 354.0 357 0 F332 0 356.0 359.0 **Die Castings** 360.0 A380.0 390.0 A413.0 A360 0 383.0 392.0 380.0 A384.0 413.0	40 to 125 500kg	As Cast or Solution Treated and Aged	3500 to 6000	100 to 250	.001 to 004	Roughing Finishing	CA46IB CA60IB	CA46GB CA60GB
			15 to 30	30 to 76	.025 to .100	Roughing Finishing	CA46IB CA60IB	CA46GB CA60GB
30. MAGNESIUM ALLOYS, WROUGHT‡‡ AZ21A AZ61A HM21A ZK60A AZ31B AZ80A HM31A AZ31C HK31A ZK40A	50 to 90 500kg	Annealed, Cold Drawn or Solution Treated and Aged	3500 to 6000	100 to 250	001 to .004	Roughing Finishing	CA46IB CA60IB	CA46GB CA60GB
			15 to 30	30 to 76	.025 to .100	Roughing Finishing	CA46IB CA60IB	CA46GB CA60GB
31. MAGNESIUM ALLOYS, CAST‡‡ AM60A AZ91A HK31A ZE63A AM100A AZ91B HZ32A ZH62A AS41A AZ91C K1A ZK51A AZ63A AZ92A QE22A ZK61A AZ81A EZ33A ZE41A	50 to 90 500kg	As Cast, Annealed or Solution Treated and Aged	3500 to 6000	100 to 250	.001 to .004	Roughing Finishing	CA46IB CA60IB	CA46GB CA60GB
			15 to 30	30 to 76	.025 to .100	Roughing Finishing	CA46IB CA60IB	CA46GB CA60GB

See section 16 for Cutting Fluid Recommendations
*See section 20.4 for calculation of Table rpm and Downfeed in ipm.

‡‡CAUTION Potential Fire Hazard. Exercise caution in grinding and disposing of swarf. Do NOT use water or water-miscible cutting fluids for magnesium alloys.

8.4 Surface Grinding-Vertical Spindle, Rotary Table

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE* (WORK) SPEED fpm m/min	DOWNFEED per rev. of table in mm	OPERATION	WHEEL IDENTIFICATION NARROW WORK AREA ANSI ISO	WHEEL IDENTIFICATION BROAD WORK AREA ANSI ISO
32. TITANIUM ALLOYS, WROUGHT‡‡			3500 to 6000	50 to 100	.0005 to .001	Roughing	C36HV	C36GV
Commercially Pure	110 to 275	Annealed				Finishing	C60IV	C60HV
99.5 99.0			18 to 30	15 to 30	.013 to .025	Roughing	C36HV	C36GV
99.2 98.9						Finishing	C60IV	C60HV
Ti-0.2Pd								
TiCODE-12								
Alpha and Alpha-Beta Alloys			3500 to 6000	50 to 100	.0005 to .001	Roughing	C36HV	C36GV
Ti-8Mn	300 to 440	Annealed or Solution Treated and Aged				Finishing	C60IV	C60HV
Ti-1Al-8V-5Fe			18 to 30	15 to 30	.013 to .025	Roughing	C36HV	C36GV
Ti-2Al-11Sn-5Zr-1Mo						Finishing	C60IV	C60HV
Ti-3Al-2.5V								
Ti-5Al-2Sn-2Zr-4Mo-4Cr (Ti-17)								
Ti-5Al-2.5Sn								
Ti-5Al-2.5Sn ELI								
Ti-5Al-6Sn-2Zr-1Mo								
Ti-6Al-2Cb-1Ta-0.8Mo								
Ti-6Al-4V								
Ti-6Al-4V ELI								
Ti-6Al-6V-2Sn								
Ti-6Al-2Sn-4Zr-2Mo								
Ti-6Al-2Sn-4Zr-2Mo-.25Si								
Ti-6Al-2Sn-4Zr-6Mo								
Ti-7Al-4Mo								
Ti-8Al-1Mo-1V								
Beta Alloys			3500 to 6000	50 to 100	.0005 to .001	Roughing	C36HV	C36GV
Ti-3Al-8V-6Cr-4Mo-4Zr	275 to 440	Annealed, Solution Treated or Solution Treated and Aged				Finishing	C60IV	C60HV
Ti-8Mo-8V-2Fe-3Al			18 to 30	15 to 30	.013 to .025	Roughing	C36HV	C36GV
Ti-11.5Mo-6Zr-4.5Sn						Finishing	C60IV	C60HV
Ti-10V-2Fe-3Al								
Ti-13V-11Cr-3Al								
33. TITANIUM ALLOYS, CAST‡‡			3500 to 6000	50 to 100	0005 to 001	Roughing	C36HV	C36GV
Commercially Pure	150 to 250	As Cast or As Cast and Annealed				Finishing	C60IV	C60HV
99.0			18 to 30	15 to 30	.013 to .025	Roughing	C36HV	C36GV
Ti-0.2Pd						Finishing	C60IV	C60HV
ASTM B367: Grades C-1, C-2, C-3, C-4, C-7A, C-7B, C-8A, C-8B								

See section 16 for Cutting Fluid Recommendations

*See section 20.4 for calculation of Table rpm and Downfeed in ipm.

‡‡CAUTION: Potential Fire Hazard. Exercise caution in grinding and disposing of swarf.

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE* (WORK) SPEED fpm m/min	DOWNFEED per rev. of table in mm	OPERATION	WHEEL IDENTIFICATION NARROW WORK AREA ANSI ISO	WHEEL IDENTIFICATION BROAD WORK AREA ANSI ISO
Alpha and Alpha-Beta Alloys Ti-5Al-2 5Sn Ti-6Al-4V Ti-6Al-2Sn-4Zr-2Mo Ti-8Al-1Mo-1V ASTM B367 Grades C-5, C-6	300 to 350	As Cast or As Cast and Annealed	3500 to 6000 18 to 30	50 to 100 15 to 30	0005 to .001 .013 to .025	Roughing Finishing Roughing Finishing	C36HV C60IV C36HV C60IV	C36GV C60HV C36GV C60HV
34. COPPER ALLOYS, WROUGHT 101 116 143 182 102 119 145 184 104 120 147 185 105 121 150 187 107 122 155 189 109 125 162 190 110 127 165 191 111 128 170†† 192 113 129 172†† 194 114 130 173†† 195 115 142 175††	10 R_B to 100 R_B	Annealed or Cold Drawn	3500 to 6000 18 to 30	100 to 250 30 to 76	.001 to .004 .025 to 100	Roughing Finishing Roughing Finishing	CA46IB CA60IB CA46IB CA60IB	CA46GB CA60GB CA46GB CA60GB
210 332 368 464 220 335 370 465 226 340 377 466 230 342 385 467 240 349 411 482 260 350 413 485 268 353 425 667 270 356 435 687 280 360 442 688 314 365 443 694 316 366 444 330 367 445	10 R_B to 100 R_B	Annealed or Cold Drawn	3500 to 6000 18 to 30	100 to 250 30 to 76	001 to .004 .025 to 100	Roughing Finishing Roughing Finishing	CA46IB CA60IB CA46IB CA60IB	CA46GB CA60GB CA46GB CA60GB
505 608 623 642 510 610 624 651 511 613 625 655 521 614 630 674 524 618 632 675 544 619 638	10 R_B to 100 R_B	Annealed or Cold Drawn	3500 to 6000 18 to 30	100 to 250 30 to 76	.001 to .004 .025 to 100	Roughing Finishing Roughing Finishing	CA46IB CA60IB CA46IB CA60IB	CA46GB CA60GB CA46GB CA60GB

See section 16 for Cutting Fluid Recommendations
*See section 20 4 for calculation of Table rpm and Downfeed in ipm.

††CAUTION. Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions

8.4 Surface Grinding-Vertical Spindle, Rotary Table

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE* (WORK) SPEED fpm m/min	DOWNFEED per rev. of table in mm	OPERATION	WHEEL IDENTIFICATION NARROW WORK AREA ANSI ISO	WHEEL IDENTIFICATION BROAD WORK AREA ANSI ISO
34. COPPER ALLOYS, WROUGHT (cont.) 706 725 754 782 710 745 757 715 752 770	10 R_B to 100 R_B	Annealed or Cold Drawn	3500 to 6000 16 to 30	100 to 250 30 to 76	.001 to .004 .025 to 100	Roughing Finishing Roughing Finishing	CA46IB CA60IB CA46IB CA60IB	CA46GB CA60GB CA46GB CA60GB
35. COPPER ALLOYS, CAST 801 811 818†† 825†† 803 813 820†† 826†† 805 814 821†† 827†† 807 815 822†† 828†† 809 817†† 824††	40 to 200 500kg	As Cast or Heat Treated	3500 to 6000 16 to 30	100 to 250 30 to 76	.001 to .004 .025 to 100	Roughing Finishing Roughing Finishing	CA46IB CA60IB CA46IB CA60IB	CA46GB CA60GB CA46GB CA60GB
833 852 862 874 834 853 863 875 836 854 864 876 838 855 865 878 842 857 867 879 844 858 868 848 861 872	35 to 200 500kg	As Cast	3500 to 6000 16 to 30	100 to 250 30 to 76	.001 to .004 .025 to 100	Roughing Finishing Roughing Finishing	CA46IB CA60IB CA46IB CA60IB	CA46GB CA60GB CA46GB CA60GB
902 916 934 948 903 917 935 952 905 922 937 953 907 923 938 954 909 925 939 955 910 926 943 956 911 927 944 957 913 928 945 958 915 932 947	40 to 100 500kg	As Cast or Heat Treated	3500 to 6000 16 to 30	100 to 250 30 to 76	001 to .004 .025 to 100	Roughing Finishing Roughing Finishing	CA46IB CA60IB CA46IB CA60IB	CA46GB CA60GB CA46GB CA60GB
962 974 963 976 964 978 966†† 993 973	50 to 100 500kg	As Cast or Heat Treated	3500 to 6000 16 to 30	100 to 250 30 to 76	.001 to .004 .025 to 100	Roughing Finishing Roughing Finishing	CA46IB CA60IB CA46IB CA60IB	CA46GB CA60GB CA46GB CA60GB
36. NICKEL ALLOYS, WROUGHT AND CAST Nickel 200 Nickel 201 Nickel 205 Nickel 211 Nickel 220 Nickel 230	80 to 170	Annealed or Cold Drawn	3500 to 4500 16 to 30	100 to 200 30 to 76	.0005 to .001 .013 to .025	Roughing Finishing Roughing Finishing	A36HV A60HV A36HV A60HV	A36GV A60GV A36GV A60GV

See section 16 for Cutting Fluid Recommendations
*See section 20.4 for calculation of Table rpm and Downfeed in ipm

††CAUTION. Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions.

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE* (WORK) SPEED fpm m/min	DOWNFEED per rev. of table in mm	OPERATION	WHEEL IDENTIFICATION NARROW WORK AREA ANSI ISO	WHEEL IDENTIFICATION BROAD WORK AREA ANSI ISO
MONEL Alloy 400 MONEL Alloy 401 MONEL Alloy 404 MONEL Alloy R405 ASTM A296 Grades CZ-100, M-35 ASTM A494. Grades CZ-100, M-35	115 to 240	Annealed, Cold Drawn or Cast	3500 to 4500	100 to 200	0005 to .001	Roughing Finishing	A36HV A60HV	A36GV A60GV
			18 to 23	30 to 60	.013 to .025	Roughing Finishing	A36HV A60HV	A36GV A60GV
DURANICKEL Alloy 301 MONEL Alloy 502 MONEL Alloy K500 NI-SPAN-C Alloy 902 PERMANICKEL Alloy 300	150 to 320	Solution Treated	3500 to 4500	100 to 200	.0005 to 001	Roughing Finishing	A36HV A60HV	A36GV A60GV
			18 to 23	30 to 60	.013 to .025	Roughing Finishing	A36HV A60HV	A36GV A60GV
	330 to 360	Aged	3500 to 4500	100 to 200	.0005 to 001	Roughing Finishing	A36GV A60GV	A36FV A60FV
			18 to 23	30 to 60	.013 to .025	Roughing Finishing	A36GV A60GV	A36FV A60FV
37. BERYLLIUM NICKEL ALLOYS, WROUGHT AND CAST†† Berylco 440 Berylco 41C Berylco 42C Berylco 43C Brush Alloy 200C Brush Alloy 220C Brush Alloy 260C	200 to 250	As Cast or Solution Treated	3000 to 3500	100 to 250	.0005 to .001	Roughing Finishing	A30HV A80HV	A30GV A80GV
			15 to 19	30 to 75	.013 to .025	Roughing Finishing	A30HV A80HV	A30GV A80GV
	283 to 425	Hardened or Aged	3000 to 3500	100 to 250	.0005 to 001	Roughing Finishing	A36GV A80GV	A36FV A80FV
			18 to 19	30 to 75	.013 to .025	Roughing Finishing	A36GV A80GV	A36FV A80FV
	47 R_C to 52 R_C	Hardened or Aged	3000 to 3500	100 to 250	.0005 to .001	Roughing Finishing	A36FV A80FV	A36EV A80EV
			18 to 19	30 to 75	.013 to .026	Roughing Finishing	A36FV A80FV	A36EV A80EV

See section 16 for Cutting Fluid Recommendations

*See section 20 4 for calculation of Table rpm and Downfeed in ipm.

††CAUTION. Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions

8.4 Surface Grinding-Vertical Spindle, Rotary Table

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE* (WORK) SPEED fpm m/min	DOWNFEED per rev. of table in mm	OPERATION	WHEEL IDENTIFICATION NARROW WORK AREA ANSI ISO	WHEEL IDENTIFICATION BROAD WORK AREA ANSI ISO
39. HIGH TEMPERATURE ALLOYS, WROUGHT AND CAST	200 to 390	Annealed or Solution Treated	3500 to 4500	100 to 200	.0005 to .001	Roughing	A36GV	A36FV
						Finishing	A60GV	A60FV
			18 to 23	30 to 60	.013 to .025	Roughing	A36GV	A36FV
						Finishing	A60GV	A60FV
Nickel Base, Wrought	300 to 475	Solution Treated and Aged	3500 to 4500	100 to 200	0005 to .001	Roughing	A36GV	A36FV
						Finishing	A60GV	A60FV
			18 to 23	30 to 60	.013 to .025	Roughing	A36GV	A36FV
						Finishing	A60GV	A60FV
AF2-1DA								
Astroloy								
Haynes Alloy 263								
IN-102								
Incoloy Alloy 901								
Incoloy Alloy 903								
Inconel Alloy 617								
Inconel Alloy 625								
Inconel Alloy 700								
Inconel Alloy 702								
Inconel Alloy 706								
Inconel Alloy 718								
Inconel Alloy 721								
Inconel Alloy 722								
Inconel Alloy X-750								
Inconel Alloy 751								
M252								
Nimonic 75								
Nimonic 80								
Nimonic 90								
Nimonic 95								
Rene 41								
Rene 63								
Rene 77								
Rene 95								
Udimet 500								
Udimet 700								
Udimet 710								
Unitemp 1753								
Waspaloy								
Nickel Base, Wrought	140 to 220	Annealed or Solution Treated	3500 to 4500	100 to 200	0005 to .001	Roughing	A36GV	A36FV
						Finishing	A60GV	A60FV
			18 to 23	30 to 60	.013 to .025	Roughing	A36GV	A36FV
						Finishing	A60GV	A60FV
Hastelloy Alloy B	240 to 310	Cold Drawn or Aged	3500 to 4500	100 to 200	.0005 to .001	Roughing	A36GV	A36FV
						Finishing	A60GV	A60FV
			18 to 23	30 to 60	.013 to .025	Roughing	A36GV	A36FV
						Finishing	A60GV	A60FV
Hastelloy Alloy B-2								
Hastelloy Alloy C								
Hastelloy Alloy C-276								
Hastelloy Alloy G								
Hastelloy Alloy S								
Hastelloy Alloy X								
Incoloy Alloy 804								
Incoloy Alloy 825								
Inconel Alloy 600								
Inconel Alloy 601								
Refractaloy 26								
Udimet 630								

See section 16 for Cutting Fluid Recommendations
*See section 20 4 for calculation of Table rpm and Downfeed in

Surface Grinding-Vertical Spindle, Rotary Table 8.4

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE* (WORK) SPEED fpm m/min	DOWNFEED per rev. of table in mm	OPERATION	WHEEL IDENTIFICATION NARROW WORK AREA ANSI ISO	WHEEL IDENTIFICATION BROAD WORK AREA ANSI ISO
Nickel Base, Cast			3500 to 4500	100 to 200	.0005 to .001	Roughing	A36GV	A36FV
B-1900	200 to 425	As Cast or Cast and Aged				Finishing	A60GV	A60FV
GMR-235			16 to 23	30 to 60	.013 to .025	Roughing	A36GV	A36FV
GMR-235D						Finishing	A60GV	A60FV
Hastelloy Alloy B								
Hastelloy Alloy C								
Hastelloy Alloy D								
IN-100 (Rene 100)								
IN-738								
IN-792								
Inconel Alloy 713C								
Inconel Alloy 718								
M252								
MAR-M200								
MAR-M246								
MAR-M421								
MAR-M432								
Rene 80								
Rene 125								
SEL								
SEL 15								
TRW VI A								
Udimet 500								
Udimet 700								
ASTM A296 Grades CW-12M, N-12M, CY-40								
ASTM A297 Grades HW, HX								
ASTM A494: Grades N-12M-1, N-12M-2, CY-40, CW-12M-1, CW-12M-2								
ASTM A608 Grades HW50, HX50								
Cobalt Base, Wrought			3000 to 4000	100 to 200	.0005 to .001	Roughing	A30GV	A30FV
AiResist 213	180 to 230	Solution Treated				Finishing	A60GV	A60FV
Haynes Alloy 25 (L605)			15 to 20	30 to 60	.013 to .025	Roughing	A30GV	A30FV
Haynes Alloy 188						Finishing	A60GV	A60FV
J-1570								
MAR-M905								
MAR-M918								
S-816	270 to 320	Solution Treated and Aged	3000 to 4000	100 to 200	.0005 to .001	Roughing	A30GV	A30FV
V-36						Finishing	A60GV	A60FV
			15 to 20	30 to 60	.013 to .025	Roughing	A30GV	A30FV
						Finishing	A60GV	A60FV

See section 16 for Cutting Fluid Recommendations
*See section 20.4 for calculation of Table rpm and Downfeed in rpm.

8.4 Surface Grinding-Vertical Spindle, Rotary Table

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	TABLE* (WORK) SPEED fpm m/min	DOWNFEED per rev. of table in mm	OPERATION	WHEEL IDENTIFICATION NARROW WORK AREA ANSI ISO	WHEEL IDENTIFICATION BROAD WORK AREA ANSI ISO
39. HIGH TEMPERATURE ALLOYS, WROUGHT AND CAST (cont.)	220 to 290	As Cast or Cast and Aged	3000 to 4000	100 to 200	0005 to 001	Roughing	A30GV	A30FV
						Finishing	A60GV	A60FV
Cobalt Base, Cast			15 to 20	30 to 60	.013 to .025	Roughing	A30GV	A30FV
AiResist 13						Finishing	A60GV	A60FV
AiResist 215								
FSX-414	290 to 425	As Cast or Cast and Aged	3000 to 4000	100 to 200	0005 to .001	Roughing	A30GV	A30FV
HS-6						Finishing	A60GV	A60FV
HS-21			15 to 20	30 to 60	.013 to .025	Roughing	A30GV	A30FV
HS-31 (X-40)						Finishing	A60GV	A60FV
HOWMET #3								
MAR-M302								
MAR-M322								
MAR-M509								
NASA Co-W-Re								
WI-52								
X-45								
Iron Base, Wrought	180 to 230	Solution Treated	3500 to 4500	100 to 200	.0005 to .001	Roughing	A36GV	A36FV
A-286						Finishing	A60GV	A60FV
Discaloy			18 to 23	30 to 60	.013 to .025	Roughing	A36GV	A36FV
Incoloy Alloy 800						Finishing	A60GV	A60FV
Incoloy Alloy 800H								
Incoloy Alloy 801								
Incoloy Alloy 802								
N-155	250 to 320	Solution Treated and Aged	3500 to 4500	100 to 200	0005 to .001	Roughing	A36GV	A36FV
V-57						Finishing	A60GV	A60FV
W-545			18 to 23	30 to 60	.013 to .025	Roughing	A36GV	A36FV
16-25-6						Finishing	A60GV	A30FV
19-9DL								

See section 16 for Cutting Fluid Recommendations
*See section 20.4 for calculation of Table rpm and Downfeed in ipm

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
1. FREE MACHINING CARBON STEELS, WROUGHT **Low Carbon Resulfurized** 1108 1118 1109 1119 1110 1211 1115 1212 1116 1213 1117 1215 **Medium Carbon Resulfurized** 1132 1140 1145 1137 1141 1146 1139 1144 1151 **Low Carbon Leaded** 10L18 12L13 12L15 11L17 12L14 **Medium Carbon Leaded** 10L45 11L37 11L44 10L50 11L41	50 R_C max	Hot Rolled, Normalized Annealed, Cold Drawn or Quenched and Tempered	5500 to 6500	70 to 100	Rough .002 Finish .0005 max.	1/2 1/6	A60LV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/2 1/8	A60LV
	Over 50 R_C	Carburized and/or Quenched and Tempered	5500 to 6500	70 to 100	Rough: .002 Finish: .0005 max.	1/4 1/6	A60KV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/4 1/6	A60KV
2. CARBON STEELS, WROUGHT **Low Carbon** 1005 1012 1019 1026 1006 1013 1020 1029 1008 1015 1021 1513 1009 1016 1022 1518 1010 1017 1023 1522 1011 1018 1025 **Medium Carbon** 1030 1042 1053 1541 1033 1043 1055 1547 1035 1044 1524 1548 1037 1045 1525 1551 1038 1046 1526 1552 1039 1049 1527 1040 1050 1536 **High Carbon** 1060 1074 1085 1566 1064 1075 1086 1572 1065 1078 1090 1069 1080 1095 1070 1084 1561	50 R_C max	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	5500 to 6500	70 to 100	Rough: .002 Finish: .0005 max.	1/2 1/6	A60LV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/2 1/8	A60LV
	Over 50 R_C	Carburized and/or Quenched and Tempered	5500 to 6500	70 to 100	Rough: .002 Finish: .0005 max.	1/4 1/8	A60KV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/4 1/8	A60KV
3. CARBON AND FERRITIC ALLOY STEELS (HIGH TEMPERATURE SERVICE) ASTM A369 Grades FPA, FPB, FP1, FP2, FP3b, FP5, FP7, FP9, FP11, FP12, FP21, FP22	150 to 200	As Forged, Annealed or Normalized and Tempered	5500 to 6500	70 to 100	Rough: .002 Finish: .0005 max.	1/2 1/6	A60LV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/2 1/8	A60LV

See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding of 2- to 4-inch [50 to 100 mm] diameter work. For DRY grinding—use a softer grade wheel. For LARGER diameter work—use a softer and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Wheel recommendations also apply to plunge grinding applications. Also see section 20.2 Grinding Guidelines.

8.5 Cylindrical Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
4. FREE MACHINING ALLOY STEELS, WROUGHT **Medium Carbon Resulfurized** 4140 4140Se 4142Te 4145Se 4147Te 4150 **Medium and High Carbon Leaded** 41L30 41L47 51L32 86L40 41L40 41L50 52L100 41L45 43L40 86L20	50 R_C max.	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	5500 to 6500	70 to 100	Rough .002 Finish .0005 max.	1/2 1/6	A60LV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/2 1/6	A60LV
	Over 50 R_C	Carburized and/or Quenched and Tempered	5500 to 6500	70 to 100	Rough .002 Finish: .0005 max	1/4 1/8	A60KV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/4 1/8	A60KV
5. ALLOY STEELS, WROUGHT **Low Carbon** 4012 4615 4817 8617 4023 4617 4820 8620 4024 4620 5015 8622 4118 4621 5115 8822 4320 4718 5120 9310 4419 4720 6118 94B15 4422 4815 8115 94B17 **Medium Carbon** 1330 4145 5132 8640 1335 4147 5135 8642 1340 4150 5140 8645 1345 4161 5145 86B45 4027 4340 5147 8650 4028 4427 5150 8655 4032 4626 5155 8660 4037 50B40 5160 8740 4042 50B44 51B60 8742 4047 5046 6150 9254 4130 50B46 81B45 9255 4135 50B50 8625 9260 4137 5060 8627 94B30 4140 50B60 8630 4142 5130 8637 **High Carbon** 50100 51100 52100 M-50	50 R_C max	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	5500 to 6500	70 to 100	Rough. .002 Finish. 0005 max	1/2 1/6	A60LV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/2 1/6	A60LV
	Over 50 R_C	Carburized and/or Quenched and Tempered	4000 to 6000	70 to 100	Rough: 002 Finish: .0004 max.	1/4 1/8	A60KV
			20 to 30	21 to 30	Rough: .050 Finish: .010 max.	1/4 1/8	A60KV

See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding of 2- to 4-inch [50 to 100 mm] diameter work. For DRY grinding—use a softer grade wheel. For LARGER diameter work—use a softer and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Wheel recommendations also apply to plunge grinding applications. Also see section 20.2, Grinding Guidelines.

MATERIAL	HARDNESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFICATION* ANSI ISO
6. HIGH STRENGTH STEELS, WROUGHT 300M 4330V 4340 4340Si 98BV40 D6ac H11 H13 HP 9-4-20 HP 9-4-25 HP 9-4-30 HP 9-4-45	50 R_C max	Annealed Normalized or Quenched and Tempered	4000 to 5500	70 to 100	Rough: .002 Finish: .0005 max.	1/2 1/6	A60KV
			20 to 28	21 to 30	Rough: .050 Finish: .013 max.	1/2 1/6	A60KV
	Over 50 R_C	Quenched and Tempered	4000 to 5500	70 to 100	Rough: .002 Finish: .0004 max.	1/4 1/8	A80IV
			20 to 28	21 to 30	Rough: .050 Finish: .010 max.	1/4 1/8	A80IV
7. MARAGING STEELS, WROUGHT ASTM A538, Grades A, B, C 120 Grade 180 Grade 200 Grade 250 Grade 300 Grade 350 Grade HY230	50 R_C max.	Annealed or Maraged	5500 to 6500	70 to 100	Rough: .002 Finish: .0005 max.	1/2 1/6	A60KV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/2 1/6	A60KV
	Over 50 R_C	Maraged	4000 to 5500	70 to 100	Rough: .002 Finish: .0005 max.	1/4 1/8	A80IV
			20 to 28	21 to 30	Rough: .050 Finish: .013 max.	1/4 1/8	A80IV
8. TOOL STEELS, WROUGHT **Group I** A2 H13 L6 P20 A3 H14 L7 P21 A4 H19 O1 S1 A6 H21 O2 S2 A8 H22 O6 S5 A9 H23 O7 S6 A10 H24 P2 S7 H10 H25 P4 W1 H11 H26 P5 W2 H12 L2 P6 W5 SAE J438b: Types W108, W109, W110, W112, W209, W210, W310	50 R_C max.	Annealed or Quenched and Tempered	5500 to 6500	60 to 100	Rough: .002 Finish: .0005 max.	1/2 1/6	A60LV
			28 to 33	18 to 30	Rough: .050 Finish: .013 max.	1/2 1/6	A60LV
	Over 50 R_C	Quenched and Tempered	4000 to 6000	60 to 100	Rough: .002 Finish: .0004 max.	1/4 1/8	A60KV
			20 to 30	18 to 30	Rough: .050 Finish: .010 max.	1/4 1/8	A60KV

See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding of 2- to 4-inch [50 to 100 mm] diameter work. For DRY grinding—use a softer grade wheel. For LARGER diameter work—use a softer and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Wheel recommendations also apply to plunge grinding applications. Also see section 20.2, Grinding Guidelines.

8.5 Cylindrical Grinding

MATERIAL	HARDNESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFICATION* ANSI ISO
8. TOOL STEELS, WROUGHT (cont.)							
Group II							
D2 H42 M42 D3 M1 T1 D4 M2 T2 D5 M3-1 T4 F1 M10 T8 F2 M39	50 R_C max	Annealed or Quenched and Tempered	5500 to 6500	60 to 100	Rough .002 Finish .0005 max	1/2 1/6	A60KV
			28 to 33	18 to 30	Rough: .050 Finish: .013 max.	1/2 1/6	A60KV
	50 R_C to 58 R_C	Quenched and Tempered	4000 to 6000	60 to 100	Rough. .002 Finish .0004 max	1/3 1/8	A60JV
			20 to 30	18 to 30	Rough: .050 Finish: .010 max.	1/3 1/8	A60JV
	Over 58 R_C	Quenched and Tempered	4000 to 5500	60 to 100	Rough: .002 Finish .0004 max.	1/4 1/8	A80IV
			20 to 28	18 to 30	Rough: .050 Finish: .010 max.	1/4 1/8	A80IV
Group III							
A7 M41 D7 M43 M3-2 M44 M6 M46 M7 M47 M33 T5 M34 T6 M36	50 R_C max.	Annealed or Quenched and Tempered	4000 to 6000	60 to 100	Rough .001 Finish. .0004 max.	1/2 1/6	A60KV
			20 to 30	18 to 30	Rough: .025 Finish: .010 max.	1/2 1/6	A60KV
	50 R_C to 58 R_C	Quenched and Tempered	4000 to 5500	60 to 100	Rough: .001 Finish: .0003 max.	1/3 1/8	A80JV
			20 to 28	18 to 30	Rough: .025 Finish: .008 max.	1/3 1/8	A80JV
	Over 58 R_C	Quenched and Tempered	4000 to 5500	60 to 100	Rough. .001 Finish: .0003 max	1/4 1/8	A80IV
			20 to 28	18 to 30	Rough: .025 Finish: .008 max.	1/4 1/8	A80IV

See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding of 2- to 4-inch [50 to 100 mm] diameter work. For DRY grinding—use a softer grade wheel. For LARGER diameter work—use a softer and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Wheel recommendations also apply to plunge grinding applications. Also see section 20.2, Grinding Guidelines.

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
Group IV M4 T15	50 R_C max	Annealed or Quenched and Tempered	4000 to 5500	60 to 100	Rough: 001 Finish: .0004 max.	1/2 1/6	A60JV
			20 to 28	18 to 30	Rough: .025 Finish: .010 max.	1/2 1/6	A60JV
	50 R_C to 58 R_C	Quenched and Tempered	4000 to 5500	60 to 100	Rough: 001 Finish .0003 max	1/3 1/8	A80IV
			20 to 28	18 to 30	Rough: .025 Finish: .008 max.	1/3 1/8	A80IV
	Over 58 R_C	Quenched and Tempered	4000 to 5000	60 to 100	Rough .001 Finish 0003 max.	1/4 1/8	A80HV
			20 to 25	18 to 30	Rough: .025 Finish: .008 max.	1/4 1/8	A80HV
9. NITRIDING STEELS, WROUGHT Nitralloy 125 Nitralloy 135 Nitralloy 135 Mod Nitralloy 225 Nitralloy 230 Nitralloy EZ Nitralloy N Nitrex 1	200 to 350	Annealed, Normalized or Quenched and Tempered	5500 to 6500	70 to 100	Rough: .001 Finish .0003 max	1/2 1/6	A60KV
			26 to 33	21 to 30	Rough: .025 Finish: .008 max.	1/2 1/6	A60KV
	60 R_C to 65 R_C	Nitrided	4000 to 5500	60 to 100	Rough .001 Finish: 0003 max	1/4 1/8	A80IV
			20 to 25	18 to 30	Rough: .025 Finish: .008 max.	1/4 1/8	A80IV
10. ARMOR PLATE, SHIP PLATE, AIRCRAFT PLATE, WROUGHT HY80 MIL-S-12560 HY100 MIL-S-16216 HY180	45 R_C max.	Annealed or Quenched and Tempered	5500 to 6500	70 to 100	Rough: 002 Finish: .0005 max.	1/2 1/6	A60JV
			26 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/2 1/6	A60JV

See section 16 for Cutting Fluid Recommendations.

*Wheel recommendations are for wet grinding of 2- to 4-inch [50 to 100 mm] diameter work. For DRY grinding—use a softer grade wheel. For LARGER diameter work—use a softer and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Wheel recommendations apply to plunge grinding applications. Also see section 20.2, Grinding Guidelines

8.5 Cylindrical Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
12. FREE MACHINING STAINLESS STEELS, WROUGHT **Ferritic** 430F 430F Se	135 to 185	Annealed	5500 to 6500	50 to 100	Rough 002 Finish .0005 max	1/2 1/6	A60JV
			28 to 33	15 to 30	Rough: .050 Finish: .013 max.	1/2 1/6	A60JV
Austenitic 203EZ 303 303MA 303Pb 303 Plus S 303Se	135 to 275	Annealed or Cold Drawn	5500 to 6500	50 to 100	Rough: .002 Finish 0005 max	1/2 1/6	C54JV
			28 to 33	15 to 30	Rough: .050 Finish: .013 max.	1/2 1/6	C54JV
Martensitic 416 416 Plus X 416Se 420F 420F Se 440F 440F Se	135 to 240	Annealed or Cold Drawn	5500 to 6500	50 to 100	Rough .002 Finish. .0005 max	1/4 1/8	A60JV
			28 to 33	15 to 30	Rough: .050 Finish: .013 max.	1/4 1/8	A60JV
	Over 275	Quenched and Tempered	5500 to 6500	50 to 100	Rough 002 Finish .0005 max	1/4 1/8	A60IV
			28 to 33	15 to 30	Rough: .050 Finish: .013 max.	1/4 1/8	A60IV
13. STAINLESS STEELS, WROUGHT **Ferritic** 405 434 409 436 429 442 430 446	135 to 185	Annealed	5500 to 6500	50 to 100	Rough .002 Finish .0005 max	1/2 1/6	A60JV
			28 to 33	15 to 30	Rough: .050 Finish: .013 max.	1/2 1/6	A60JV
Austenitic 201 308 317 202 309 321 301 309S 330 302 310 347 302B 310S 348 304 314 384 304L 316 385 305 316L	135 to 275	Annealed or Cold Drawn	5500 to 6500	50 to 100	Rough. .002 Finish 0005 max.	1/2 1/6	C54JV
			28 to 33	15 to 30	Rough: .050 Finish: .013 max.	1/2 1/6	C54JV

See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding of 2- to 4-inch [50 to 100 mm] diameter work. For DRY grinding—use a softer grade wheel. For LARGER diameter work—use a softer and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Wheel recommendations also apply to plunge grinding applications. Also see section 20.2, Grinding Guidelines.

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
Austenitic Nitronic 32 Nitronic 33 Nitronic 40 Nitronic 50 Nitronic 60	210 to 250	Annealed	5500 to 6500	50 to 100	Rough .002 Finish .0005 max	1/2 1/6	C54JV
			28 to 33	15 to 30	Rough: .050 Finish: .013 max.	1/2 1/6	C54JV
	325 to 375	Cold Drawn	5500 to 6500	50 to 100	Rough .002 Finish .0005 max.	1/4 1/8	C54IV
			28 to 33	15 to 30	Rough: .050 Finish: .013 max.	1/4 1/8	C54IV
Martensitic 403 440A 410 440B 414 440C 420 501 422 502 431 Greek Ascoloy	135 to 275	Annealed	5500 to 6500	50 to 100	Rough .002 Finish: .0005 max	1/4 1/8	A60JV
			28 to 33	15 to 30	Rough: .050 Finish: .013 max.	1/4 1/8	A60JV
	Over 275	Quenched and Tempered	5500 to 6500	50 to 100	Rough. .002 Finish: .0005 max.	1/4 1/8	A60IV
			28 to 33	15 to 30	Rough: .050 Finish: .013 max.	1/4 1/8	A60IV
14. PRECIPITATION HARDENING STAINLESS STEELS, WROUGHT 15-5 PH 16-6 PH 17-4 PH 17-7 PH 17-14 Cu Mo AF-71 AFC-77 Almar 362 (AM-362) AM-350 AM-355 AM-363 Custom 450 Custom 455 HNM PH 13-8 Mo PH 14-8 Mo PH 15-7 Mo Stainless W	150 to 200	Solution Treated	5500 to 6500	70 to 100	Rough .002 Finish .0005 max	1/4 1/8	A60JV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/4 1/8	A60JV
	275 to 440	Solution Treated or Hardened	5500 to 6500	70 to 100	Rough .002 Finish: .0005 max.	1/4 1/8	A60IV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/4 1/8	A60IV

See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding of 2- to 4-inch [50 to 100 mm] diameter work. For DRY grinding—use a softer grade wheel. For LARGER diameter work—use a softer and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Wheel recommendations also apply to plunge grinding applications. Also see section 20.2, Grinding Guidelines.

8.5 Cylindrical Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
15. CARBON STEELS, CAST **Low Carbon** ASTM A426. Grade CP1 1010 1020 **Medium Carbon** ASTM A352. Grades LCA, LCB, LCC ASTM A356. Grade 1 1030 1040 1050	100 to 300	Annealed, Normalized, Normalized and Tempered, or Quenched and Tempered	5500 to 6500	70 to 100	Rough .002 Finish .0005 max.	1/2 1/6	A60LV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/2 1/6	A60LV
	Over 50 R_C	Carburized and/or Quenched and Tempered	5500 to 6500	70 to 100	Rough .002 Finish .0005 max	1/4 1/8	A60KV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/4 1/8	A60KV
16. ALLOY STEELS, CAST **Low Carbon** ASTM A217. Grade WC9 ASTM A352 Grades LC3, LC4 ASTM A426. Grades CP2, CP5, CP5b, CP11, CP12, CP15, CP21, CP22 1320 4110 8020 2315 4120 8620 2320 4320 **Medium Carbon** ASTM A27: Grades N1, N2, U-60-30, 60-30, 65-35, 70-36, 70-40 ASTM A148. Grades 80-40, 80-50, 90-60, 105-85, 120-95, 150-125, 175-145 ASTM A216 Grades WCA, WCB, WCC ASTM A217: Grades WC1, WC4, WC5, WC6 ASTM A352. Grades LC1, LC2, LC2-1 ASTM A356 Grades 2, 5, 6, 8, 9, 10 ASTM A389: Grades C23, C24 ASTM A486. Classes 70, 90, 120 ASTM A487 Classes 1N, 2N, 4N, 6N, 8N, 9N, 10N, DN, 1Q, 2Q, 4Q, 4QA, 6Q, 7Q, 8Q, 9Q, 10Q 1330 4130 80B30 8640 1340 4140 8040 9525 2325 4330 8430 9530 2330 4340 8440 9535 4125 8030 8630	150 to 400	Annealed, Normalized, Normalized and Tempered, or Quenched and Tempered	5500 to 6500	70 to 100	Rough .002 Finish .0005 max.	1/2 1/6	A60LV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/2 1/6	A60LV
	Over 50 R_C	Carburized and/or Quenched and Tempered	4000 to 6000	70 to 100	Rough: 002 Finish .0005 max	1/4 1/8	A60KV
			20 to 30	21 to 30	Rough: .050 Finish: .013 max.	1/4 1/8	A60KV

See section 16 for Cutting Fluid Recommendations.

*Wheel recommendations are for wet grinding of 2- to 4-inch [50 to 100 mm] diameter work. For DRY grinding—use a softer grade wheel. For LARGER diameter work—use a softer and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Wheel recommendations also apply to plunge grinding applications. Also see section 20.2, Grinding Guidelines.

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
17. TOOL STEELS, CAST **Group I** ASTM A597. Grades CA-2, CH-12, CH-13, CO-1, CS-5	50 R_C max	Annealed or Quenched and Tempered	4000 to 6000	60 to 100	Rough: .002 Finish: .0005 max.	1/2 1/6	A60LV
			20 to 30	18 to 30	Rough: .050 Finish: .013 max.	1/2 1/6	A60LV
	50 R_C to 58 R_C	Quenched and Tempered	4000 to 5500	60 to 100	Rough: .002 Finish: 0004 max.	1/3 1/8	A60KV
			20 to 28	18 to 30	Rough: .050 Finish: .010 max.	1/3 1/8	A60KV
	Over 58 R_C	Quenched and Tempered	4000 to 5500	60 to 100	Rough: .002 Finish. .0004 max	1/4 1/8	A60JV
			20 to 28	18 to 30	Rough: .050 Finish: .010 max.	1/4 1/8	A60JV
Group II ASTM A597: Grades CD-2, CD-5	200 to 250	Annealed	4000 to 6000	60 to 100	Rough: .002 Finish: .0005 max.	1/2 1/6	A60LV
			20 to 30	18 to 30	Rough: .050 Finish: .013 max.	1/2 1/6	A60LV
	48 R_C to 56 R_C	Quenched and Tempered	4000 to 5500	60 to 100	Rough: .002 Finish: .0004 max.	1/3 1/8	A60KV
			20 to 28	18 to 30	Rough: .050 Finish: .010 max.	1/3 1/8	A60KV
	Over 56 R_C	Quenched and Tempered	4000 to 5500	60 to 100	Rough: .002 Finish: 0003 max	1/4 1/8	A80JV
			20 to 28	18 to 30	Rough: .050 Finish: .010 max.	1/4 1/8	A80JV

See section 16 for Cutting Fluid Recommendations.

*Wheel recommendations are for wet grinding of 2- to 4-inch [50 to 100 mm] diameter work. For DRY grinding—use a softer grade wheel For LARGER diameter work—use a softer and/or coarser grit wheel For SMALLER diameter work—use a harder grade wheel Wheel recommendations also apply to plunge grinding application Also see section 20 2, Grinding Guidelines

8.5 Cylindrical Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
18. STAINLESS STEELS, CAST **Ferritic** ASTM A217 Grades C5, C12 ASTM A296· Grades CB-30, CC-50, CE-30, CA6N, CA-6NM, CD4MCu ASTM A297 Grade HC ASTM A487· Class CA6NM ASTM A608· Grade HC30	135 to 185	Annealed	5500 to 6500	50 to 100	Rough: 002 Finish: 0005 max.	1/2 1/6	A60JV
			28 to 33	15 to 30	Rough: 050 Finish: 013 max.	1/2 1/6	A60JV
Austenitic ASTM A296 Grades CF-3, CF-3M, CF-8, CF-8C, CF-8M, CF-16F, CF-20, CG-8M, CG-12, CH-20, CK-20, CN-7M, CN-7MS ASTM A297· Grades HD, HE, HF, HH, HI, HK, HL, HN, HP, HT, HU ASTM A351 Grades CF-3, CF-3A, CF-3M, CF-3MA, CF-8, CF-8A, CF-8C, CF-8M, CF-10MC, CH-8, CH-10, CH-20, CK-20, CN-7M, HK-30, HK-40, HT-30 ASTM A451· Grades CPF8A, CPF3, CPF3A, CPF3M, CPF8, CPF8C, CPF8C (Ta Max), CPF8M, CPF10MC, CPH8, CPH10, CPH20, CPK20 ASTM A452 Grades TP 304H, TP 316H, TP 347H ASTM A608 Grades HD50, HE35, HF30, HH30, HH33, HI35, HK30, HK40, HL30, HL40, HN40, HT50, HU50	135 to 210	Annealed, Normalized or As Cast	5500 to 6500	50 to 100	Rough: 002 Finish .0005 max	1/2 1/6	C54JV
			28 to 33	15 to 30	Rough: 050 Finish: 013 max.	1/2 1/6	C54JV
Martensitic ASTM A217· Grade CA-15 ASTM A296: Grades CA-15, CA-15M, CA-40 ASTM A426. Grades CP7, CP9, CPCA15 ASTM A487. Classes CA15a, CA-15M	135 to 225	Annealed, Normalized or Normalized and Tempered	5500 to 6500	50 to 100	Rough: 002 Finish· 0005 max	1/4 1/8	A60JV
			28 to 33	15 to 30	Rough: 050 Finish: 013 max.	1/4 1/8	A60JV
	Over 275	Quenched and Tempered	5500 to 6500	50 to 100	Rough. .002 Finish: 0005 max.	1/4 1/8	A60IV
			28 to 33	15 to 30	Rough: 050 Finish: 013 max.	1/4 1/8	A60IV

See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding of 2- to 4-inch [50 to 100 mm] diameter work For DRY grinding—use a softer grade wheel For LARGER diameter work—use a softer and/or coarser grit wheel For SMALLER diameter work—use a harder grade wheel Wheel recommendations also apply to plunge grinding applications. Also see section 20 2, Grinding Guidelines

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
19. PRECIPITATION HARDENING STAINLESS STEELS, CAST ASTM A351 Grade CD-4MCu ACI Grade CB-7Cu ACI Grade CD-4MCu 17-4 PH AM-355	325 to 450	Solution Treated or Solution Treated and Aged	5500 to 6500	70 to 100	Rough 002 Finish 0005 max	1/4 1/8	A60IV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/4 1/8	A60IV
21. GRAY CAST IRONS **Ferritic** ASTM A48 Class 20 SAE J431c Grade G1800 **Pearlitic- Ferritic** ASTM A48 Class 25 SAE J431c Grade G2500 **Pearlitic** ASTM A48. Classes 30, 35, 40 SAE J431c. Grade G3000 **Pearlitic + Free Carbides** ASTM A48 Classes 45, 50 SAE J431c Grades G3500, G4000 **Pearlitic or Acicular + Free Carbides** ASTM A48 Classes 55, 60	45 R_C max	As Cast, Annealed or Quenched and Tempered	5500 to 6500	70 to 100	Rough .002 Finish: .001 max	1/2 1/6	C46KV
			28 to 33	21 to 30	Rough: .050 Finish: .025 max.	1/2 1/6	C46KV
	45 R_C to 52 R_C	As Cast, Annealed or Quenched and Tempered	5500 to 6500	70 to 100	Rough 002 Finish: 0005 max	1/3 1/6	C54JV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/3 1/6	C54JV
	48 R_C to 60 R_C	Flame or Induction Hardened	5500 to 6500	70 to 100	Rough: 002 Finish. 0005 max	1/4 1/8	C60Iv
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/4 1/8	C60IV
Austenitic (NI-RESIST) ASTM A436 Types 1, 1b, 2, 2b, 3, 4, 5, 6	100 to 250	As Cast	5500 to 6500	40 to 65	Rough 002 Finish. .0005 max.	1/2 1/6	A60KV
			28 to 33	12 to 20	Rough: .050 Finish: .013 max.	1/2 1/6	A60KV
22. COMPACTED GRAPHITE CAST IRONS	185 to 225	As Cast	5500 to 6500	70 to 100	Rough .002 Finish .001 max.	1/2 1/6	C46KV
			28 to 33	21 to 30	Rough: .050 Finish: .025 max.	1/2 1/6	C46KV

See section 16 for Cutting Fluid Recommendations

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8.5 Cylindrical Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
23. DUCTILE CAST IRONS **Ferritic** ASTM A536 Grades 60-40-18, 65-45-12 SAE J434c Grades D4018, D4512 **Ferritic- Pearlitic** ASTM A536 Grade 80-55-06 SAE J434c, Grade D5506 **Pearlitic- Martensitic** ASTM A536: Grade 100-70-03 SAE J434c Grade D7003 **Martensitic** ASTM A536 Grade 120-90-02 SAE J434c Grade DQ&T	52 R_C max	Annealed, As Cast Normalized and Tempered or Quenched and Tempered	5500 to 6500	70 to 100	Rough: .002 Finish: .0005 max	1/4 1/8	C54JV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/4 1/8	C54JV
	53 R_C to 60 R_C	Flame or Induction Hardened	5500 to 6500	70 to 100	Rough: 002 Finish: .0005 max	1/4 1/8	C60IV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/4 1/8	C60IV
Austenitic (NI-RESIST Ductile) ASTM A439, Types D-2, D-2B, D-2C, D-3, D-3A, D-4, D-5, D-5B ASTM A571: Type D-2M	120 to 275	Annealed	5500 to 6500	40 to 65	Rough: .002 Finish: .0005 max.	1/2 1/6	A60LV
			25 to 33	12 to 20	Rough: .050 Finish: .013 max.	1/2 1/6	A60LV
24. MALLEABLE CAST IRONS **Ferritic** ASTM A47, Grades 32510, 35018 ASTM A602: Grade M3210 SAE J158: Grade M3210 **Pearlitic** ASTM A220, Grades 40010, 45006, 45008, 50005 ASTM A602: Grade M4504, M5003 SAE J158: Grades M4504, M5003 **Tempered Martensite** ASTM A220 Grades 60004, 70003, 80002, 90001 ASTM A602: Grades M5503, M7002, M8501 SAE J158 Grades M5503, M7002, M8501	52 R_C max	Malleablized or Malleablized and Heat Treated	5500 to 6500	70 to 100	Rough: .002 Finish: .0005 max.	1/3 1/6	C54JV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/3 1/6	C54JV
	Over 52 R_C	Flame or Induction Hardened	5500 to 6500	70 to 100	Rough: .002 Finish, 0005 max.	1/4 1/8	C60IV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/4 1/8	C60IV
25. WHITE CAST IRONS (ABRASION RESISTANT) ASTM A532: Class I, Types A, B, C, D Class II, Types A, B, C, D, E Class III, Type A	60 R_C max	As Cast, Annealed or Hardened	5500 to 6500	70 to 100	Rough: .002 Finish: .0005 max.	1/4 1/8	C60IV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/4 1/8	C60IV

See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding of 2- to 4-inch [50 to 100 mm] diameter work. For DRY grinding—use a softer grade wheel. For LARGER diameter work—use a softer and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Wheel recommendations also apply to plunge grinding applications. Also see section 20.2, Grinding Guidelines.

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
26. HIGH SILICON CAST IRONS Duriron Duriclor ASTM A518	52 R_C	As Cast	5500 to 6500	70 to 100	Rough .002 Finish 0005 max	1/4 1/8	Rough C36KB Finish C60LB
			28 to 33	21 to 30	Rough: .050 Finish: .013 max	1/4 1/8	Rough: C36KB Finish: C60LB
27. CHROMIUM-NICKEL ALLOY CASTINGS ASTM A560 Grades 50Cr-50Ni, 50Cr-40Ni	275 to 375	As Cast	5500 to 6500	50 to 100	Rough .002 Finish .0005 max	1/4 1/8	C54IV
			28 to 33	15 to 30	Rough: .050 Finish: .013 max	1/4 1/8	C54IV
28. ALUMINUM ALLOYS, WROUGHT EC 2218 5252 6253 1060 2219 5254 6262 1100 2618 5454 6463 1145 3003 5456 6951 1175 3004 5457 7001 1235 3005 5652 7004 2011 4032 5657 7005 2014 5005 6053 7039 2017 5050 6061 7049 2018 5052 6063 7050 2021 5056 6066 7075 2024 5083 6070 7079 2025 5086 6101 7175 2117 5154 6151 7178	30 to 150 500kg	Cold Drawn or Solution Treated and Aged	5500 to 6500	50 to 150	Rough .002 Finish .0005 max	1/3 1/6	C54JV†
			28 to 33	15 to 46	Rough: .050 Finish: .013 max	1/3 1/6	C54JV†
29. ALUMINUM ALLOYS, CAST **Sand and Permanent Mold** A140 295.0 514.0 A712.0 201.0 B295.0 A514.0 D712.0 208.0 308.0 B514.0 713.0 213.0 319.0 520.0 771.0 222.0 355.0 535.0 850.0 224.0 C355.0 705.0 A850.0 242.0 B443.0 707.0 B850.0 Hiduminium RR-350 **Die Castings** C443.0 518.0	40 to 125 500kg	As Cast or Solution Treated and Aged	5500 to 6500	50 to 150	Rough .002 Finish .0005 max.	1/3 1/6	C54JV†
			28 to 33	15 to 46	Rough: .050 Finish: .013 max	1/3 1/6	C54JV†

See section 16 for Cutting Fluid Recommendations

†Wax filled

*Wheel recommendations are for wet grinding of 2- to 4-inch [50 to 100 mm] diameter work. For DRY grinding—use a softer grade wheel
For LARGER diameter work—use a softer and/or coarser grit wheel
For SMALLER diameter work—use a harder grade wheel. Wheel recommendations also apply to plunge grinding applications. Also see section 20.2, Grinding Guidelines

8.5 Cylindrical Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
29. ALUMINUM ALLOYS, CAST (cont.) **Sand and Permanent Mold** 328.0 356.0 A332.0 A356.0 F332.0 357.0 333.0 359.0 354.0 **Die Castings** 360.0 A380.0 390.0 A413.0 A360.0 383.0 392.0 380.0 A384.0 413.0	40 to 125 500kg	As Cast or Solution Treated and Aged	5500 to 6500 28 to 33	50 to 150 15 to 46	Rough: .002 Finish .0005 max Rough: .050 Finish: .013 max.	1/3 1/6 1/3 1/6	A54IV A54IV
30. MAGNESIUM ALLOYS, WROUGHT‡‡ AZ21A HK31A AZ31B HM21A AZ31C HM31A AZ61A ZK40A AZ80A ZK60A	50 to 90 500kg	Annealed, Cold Drawn or Solution Treated and Aged	5500 to 6500 28 to 33	70 to 150 21 to 46	Rough: .002 Finish: .0005 max Rough: .050 Finish: .013 max.	1/3 1/6 1/3 1/6	C60KV C60KV
31. MAGNESIUM ALLOYS, CAST‡‡ AM60A AZ91C ZE41A AM100A AZ92A ZE63A AS41A EZ33A ZH62A AZ63A HK31A ZK51A AZ81A HZ32A ZK61A AZ91A K1A AZ91B QE22A	50 to 90 500kg	As Cast, Annealed or Solution Treated and Aged	5500 to 6500 25 to 33	70 to 150 21 to 46	Rough: .002 Finish: .0005 max. Rough: .050 Finish: .013 max.	1/3 1/6 1/3 1/6	C60KV C60KV
32. TITANIUM ALLOYS, WROUGHT‡‡ **Commercially Pure** 99.5 99.2 99.0 98.9 Ti-0.2Pd TiCODE-12	110 to 275	Annealed	3000 to 4000 15 to 20	50 to 100 15 to 30	Rough .001 Finish. .0005 max. Rough: .025 Finish: .013 max.	1/5 1/10 1/5 1/10	C60JV‡ C60JV‡

See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding of 2- to 4-inch [50 to 100 mm] diameter work. For DRY grinding—use a softer grade wheel. For LARGER diameter work—use a softer and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Wheel recommendations also apply to plunge grinding applications. Also see section 20.2, Grinding Guidelines.

‡ Use friable (green grit) silicon carbide

‡‡ CAUTION: Potential Fire Hazard. Exercise caution in grinding and disposing of swarf. Do NOT use water or water-miscible cutting fluids for magnesium alloys.

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
Alpha and Alpha-Beta Alloys Ti-8Mn Ti-1Al-8V-5Fe Ti-2Al-11Sn-5Zr-1Mo Ti-3Al-2 5V Ti-5Al-2Sn-2Zr-4Mo-4Cr (Ti-17) Ti-5Al-2.5Sn Ti-5Al-2 5Sn ELI Ti-5Al-6Sn-2Zr-1Mo Ti-6Al-2Cb-1Ta-0 8Mo Ti-6Al-4V Ti-6Al-4V ELI Ti-6Al-6V-2Sn Ti-6Al-2Sn-4Zr-2Mo Ti-6Al-2Sn-4Zr-2Mo- 25Si Ti-6Al-2Sn-4Zr-6Mo Ti-7Al-4Mo Ti-8Al-1Mo-1V	300 to 380	Annealed	3000 to 4000	50 to 100	Rough: .001 Finish: 0005 max.	1/5 1/10	C60JV‡
			15 to 20	15 to 30	Rough: .025 Finish: .013 max.	1/5 1/10	C60JV‡
	320 to 440	Solution Treated and Aged	3000 to 4000	50 to 100	Rough: .001 Finish: .0005 max.	1/5 1/10	C60JV‡
			15 to 20	15 to 30	Rough: .025 Finish: .013 max.	1/5 1/10	C60JV‡
Beta Alloys Ti-3Al-8V-6Cr-4Mo-4Zr Ti-8Mo-8V-2Fe-3Al Ti-11 5Mo-6Zr-4.5Sn Ti-10V-2Fe-3Al Ti-13V-11Cr-3Al	275 to 350	Annealed or Solution Treated	3000 to 4000	50 to 100	Rough: .001 Finish: .0005 max.	1/5 1/10	C60JV‡
			15 to 20	15 to 30	Rough: .025 Finish: .013 max.	1/5 1/10	C60JV‡
	350 to 440	Solution Treated and Aged	3000 to 4000	50 to 100	Rough: .001 Finish: .0005 max.	1/5 1/10	C60JV‡
			15 to 20	15 to 30	Rough: .025 Finish: .013 max.	1/5 1/10	C60JV‡
33. TITANIUM ALLOYS, CAST‡‡ **Commercially Pure** 99 0 Ti-0 2Pd ASTM B367 Grades C-1, C-2, C-3, C-4, C-7A, C-7B, C-8A, C-8B	150 to 250	As Cast or As Cast and Annealed	3000 to 4000	50 to 100	Rough: .001 Finish .0005 max.	1/5 1/10	C60JV‡
			15 to 20	15 to 30	Rough: .025 Finish: .013 max.	1/5 1/10	C60JV‡
Alpha and Alpha-Beta Alloys Ti-5Al-2.5Sn Ti-6Al-4V Ti-6Al-2Sn-4Zr-2Mo Ti-8Al-1Mo-1V ASTM B367: Grades C-5, C-6	300 to 350	As Cast or As Cast and Annealed	3000 to 4000	50 to 100	Rough: .001 Finish: .0005 max.	1/5 1/10	C60JV‡
			15 to 20	15 to 30	Rough: .025 Finish: .013 max.	1/5 1/10	C60JV‡

See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding of 2- to 4-inch [50 to 100 mm] diameter work For DRY grinding—use a softer grade wheel For LARGER diameter work—use a softer and/or coarser grit wheel For SMALLER diameter work—use a harder grade wheel Wheel recommendations also apply to plunge grinding applications Also see section 20 2, Grinding Guidelines

‡Use friable (green grit) silicon carbide

‡‡CAUTION Potential Fire Hazard. Exercise caution in grinding and disposing of swarf

8.5 Cylindrical Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
34. COPPER ALLOYS, WROUGHT							
101 116 143 182 102 119 145 184 104 120 147 185 105 121 150 187 107 122 155 189 109 125 162 190 110 127 165 191 111 128 170†† 192 113 129 172†† 194 114 130 173†† 195 115 142 175††	10 R_B to 70 R_B	Annealed	5500 to 6500	70 to 100	Rough: .002 Finish: .0005 max	1/3 1/6	C46JV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/3 1/6	C46JV
	60 R_B to 100 R_B	Cold Drawn	5500 to 6500	70 to 100	Rough: .002 Finish: .0005 max	1/3 1/6	C46JV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/3 1/6	C46JV
210 332 368 464 220 335 370 465 226 340 377 466 230 342 385 467 240 349 411 482 260 350 413 485 268 353 425 667 270 356 435 687 280 360 442 688 314 365 443 694 316 366 444 330 367 445	10 R_B to 70 R_B	Annealed	5500 to 6500	70 to 100	Rough: .002 Finish: .0005 max	1/3 1/6	C46KV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/3 1/6	C46KV
	60 R_B to 100 R_B	Cold Drawn	5500 to 6500	70 to 100	Rough: .002 Finish: .0005 max	1/3 1/6	C46KV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/3 1/6	C46KV
505 613 632 510 614 638 511 618 642 521 619 651 524 623 655 544 624 674 608 625 675 610 630	10 R_B to 70 R_B	Annealed	5500 to 6500	70 to 100	Rough: .002 Finish: .0005 max.	1/3 1/6	C46KV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/3 1/6	C46KV
	60 R_B to 100 R_B	Cold Drawn	5500 to 6500	70 to 100	Rough: .002 Finish: .0005 max.	1/3 1/6	C46KV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/3 1/6	C46KV

See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding of 2- to 4-inch (50 to 100 mm) diameter work. For DRY grinding—use a softer grade wheel. For LARGER diameter work—use a softer and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Wheel recommendations also apply to plunge grinding applications. Also see section 20.2, Grinding Guidelines.

††CAUTION: Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions.

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
706 752 710 754 715 757 725 770 745 782	10 R_B to 70 R_B	Annealed	5500 to 6500	70 to 100	Rough .002 Finish .0005 max.	1/3 1/6	C46KV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/3 1/6	C46KV
	60 R_B to 100 R_B	Cold Drawn	5500 to 6500	70 to 100	Rough: .002 Finish. .0005 max.	1/3 1/6	C46KV
			28 to 33	21 to 30	Rough: .050 Finish .013 max.	1/3 1/6	C46KV
35. COPPER ALLOYS, CAST 801 814 824†† 803 815 825†† 805 817†† 826†† 807 818†† 827†† 809 820†† 828†† 811 821†† 813 822††	40 to 200 500kg	As Cast or Heat Treated	5500 to 6500	70 to 100	Rough: .002 Finish: .0005 max.	1/3 1/6	C46JV
			28 to 33	21 to 30	Rough: .050 Finish .013 max.	1/3 1/6	C46JV
	34 R_C to 45 R_C	Heat Treated	5500 to 6500	70 to 100	Rough: .002 Finish: .0005 max.	1/3 1/6	A54LV
			28 to 33	21 to 30	Rough: .050 Finish .013 max.	1/3 1/6	A54LV
833 854 867 834 855 868 836 857 872 838 858 874 842 861 875 844 862 876 848 863 878 852 864 879 853 865	35 to 200 500kg	As Cast	5500 to 6500	70 to 100	Rough .002 Finish .0005 max.	1/3 1/6	C46KV
			28 to 33	21 to 30	Rough: .050 Finish .013 max.	1/3 1/6	C46KV
902 916 934 948 903 917 935 952 905 922 937 953 907 923 938 954 909 925 939 955 910 926 943 956 911 927 944 957 913 928 945 958 915 932 947	40 to 100 500kg	As Cast	5500 to 6500	70 to 100	Rough: .002 Finish: .0005 max.	1/3 1/6	C46KV
			28 to 33	21 to 30	Rough: .050 Finish .013 max.	1/3 1/6	C46KV

See section 16 for Cutting Fluid Recommendations.

*Wheel recommendations are for wet grinding of 2- to 4-inch [50 to 100 mm] diameter work. For DRY grinding—use a softer grade wheel. For LARGER diameter work—use a softer and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Wheel recommendations also apply to plunge grinding applications. Also see section 20.2, Grinding Guidelines.

††CAUTION: Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions.

8.5 Cylindrical Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
35. COPPER ALLOYS, CAST (cont.) (materials listed on preceding page)	Over 100 500kg	As Cast or Heat Treated	5500 to 6500	70 to 100	Rough .002	1/3	A54LV
					Finish 0005 max.	1/6	
			28 to 33	**21 to 30**	**Rough: .050**	**1/3**	**A54LV**
					Finish: .013 max.	**1/6**	
962 963 964 966†† 973 974 976 978 993	50 to 100 500kg	As Cast	5500 to 6500	70 to 100	Rough .002	1/3	C46KV
					Finish 0005 max	1/6	
			28 to 33	**21 to 30**	**Rough: .050**	**1/3**	**C46KV**
					Finish: .013 max.	**1/6**	
	Over 100 500kg	As Cast or Heat Treated	5500 to 6500	70 to 100	Rough. .002	1/3	A54LV
					Finish .0005 max.	1/6	
			28 to 33	**21 to 30**	**Rough: .050**	**1/3**	**A54LV**
					Finish: .013 max.	**1/6**	
36. NICKEL ALLOYS, WROUGHT AND CAST Nickel 200 Nickel 201 Nickel 205 Nickel 211 Nickel 220 Nickel 230	80 to 170	Annealed or Cold Drawn	5500 to 6500	50 to 100	Rough: 002	1/5	C54JV
					Finish. .0005 max	1/10	
			28 to 33	**15 to 30**	**Rough: .050**	**1/5**	**C54JV**
					Finish: .013 max.	**1/10**	
MONEL Alloy 400 MONEL Alloy 401 MONEL Alloy 404 MONEL Alloy R405 ASTM A296: Grades CZ-100, M-35 ASTM A494: Grades CZ-100, M-35	115 to 240	Annealed, Cold Drawn or Cast	5500 to 6500	50 to 100	Rough: .002	1/5	C54JV
					Finish. .0005 max.	1/10	
			28 to 33	**15 to 30**	**Rough: .050**	**1/5**	**C54JV**
					Finish: .013 max.	**1/10**	
DURANICKEL Alloy 301 MONEL Alloy 502 MONEL Alloy K500 NI-SPAN-C Alloy 902 PERMANICKEL Alloy 300	150 to 320	Solution Treated	5500 to 6500	50 to 100	Rough .002	1/5	C60JV
					Finish .0005 max.	1/10	
			28 to 33	**15 to 30**	**Rough: .050**	**1/5**	**C60JV**
					Finish: .013 max.	**1/10**	

See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding of 2- to 4-inch (50 to 100 mm) diameter work. For DRY grinding—use a softer grade wheel. For LARGER diameter work—use a softer and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Wheel recommendations also apply to plunge grinding applications. Also see section 20.2, Grinding Guidelines.

††CAUTION: Toxic Material: refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions.

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
36. NICKEL ALLOYS, WROUGHT AND CAST (cont.) (materials listed on preceding page)	330 to 360	Aged	5500 to 6500	50 to 100	Rough .002 Finish .0005 max	1/5 1/10	C60JV
			28 to 33	15 to 30	Rough: .050 Finish: .013 max.	1/5 1/10	C60JV
37. BERYLLIUM NICKEL ALLOYS, WROUGHT AND CAST†† Berylco 440 Berylco 41C Berylco 42C Berylco 43C Brush Alloy 200C Brush Alloy 220C Brush Alloy 260C	200 to 250	As Cast or Solution Treated	5500 to 6500	50 to 100	Rough .002 Finish: .0005 max.	1/5 1/10	A60KV
			28 to 33	15 to 30	Rough .050 Finish: .013 max.	1/5 1/10	A60KV
	283 to 425	Hardened or Aged	5500 to 6500	50 to 100	Rough .002 Finish. .0005 max.	1/5 1/10	A60JV
			28 to 33	15 to 30	Rough: .050 Finish. .013 max.	1/5 1/10	A60JV
	47 R_C to 52 R_C	Hardened or Aged	5500 to 6500	50 to 100	Rough: .002 Finish .0005 max.	1/5 1/10	A60IV
			28 to 33	15 to 30	Rough: .050 Finish: .013 max.	1/5 1/10	A60IV
38. NITINOL ALLOYS, WROUGHT Nitinol 55Ni-45Ti Nitinol 56Ni-44Ti Nitinol 60Ni-40Ti	210 to 340	Wrought or Annealed	5000	50 to 100	Rough: .002 Finish. .0005 max.	1/5 1/10	C60JV
			25	15 to 30	Rough .050 Finish .013 max.	1/5 1/10	C60JV
	48 R_C to 52 R_C	Quenched	5000	50 to 100	Rough. .002 Finish: .0005 max.	1/5 1/10	C60IV
			25	15 to 30	Rough .060 Finish .013 max.	1/5 1/10	C60IV

See section 15 — Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding of 2- to 4-inch (50 to 100 mm) diameter work. For DRY grinding—use a softer grade wheel. For LARGER diameter work—use a softer and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Wheel recommendations also apply to plunge grinding applications. Also see section 20-2, Grinding Guidelines.

††CAUTION Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions

8.5 Cylindrical Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
39. HIGH TEMPERATURE ALLOYS, WROUGHT AND CAST							
Nickel Base, Wrought							
AF2-1DA	200 to 390	Annealed or Solution Treated	3000 to 3500	50 to 100	Rough .001	1/5	A60JV
Astroloy					Finish .0002 max	1/10	
Haynes Alloy 263			15 to 18	15 to 30	Rough .025	1/5	A60JV
IN-102					Finish .005 max	1/10	
Incoloy Alloy 901							
Incoloy Alloy 903							
Inconel Alloy 617							
Inconel Alloy 625	300 to 475	Solution Treated and Aged	3000 to 3500	50 to 100	Rough .001	1/5	A60JV
Inconel Alloy 700					Finish .0002 max.	1/10	
Inconel Alloy 702							
Inconel Alloy 706							
Inconel Alloy 718			15 to 18	15 to 30	Rough .025	1/5	A60JV
Inconel Alloy 721					Finish .006 max.	1/10	
Inconel Alloy 722							
Inconel Alloy X-750							
Inconel Alloy 751							
M252							
Nimonic 75							
Nimonic 80							
Nimonic 90							
Nimonic 95							
Rene 41							
Rene 63							
Rene 77							
Rene 95							
Udimet 500							
Udimet 700							
Udimet 710							
Unitemp 1753							
Waspaloy							
Nickel Base, Wrought							
Hastelloy Alloy B	140 to 220	Annealed or Solution Treated	3000 to 3500	50 to 100	Rough .001	1/5	A60JV
Hastelloy Alloy B-2					Finish .0002 max	1/10	
Hastelloy Alloy C							
Hastelloy Alloy C-276							
Hastelloy Alloy G			15 to 18	15 to 30	Rough .025	1/5	A60JV
Hastelloy Alloy S					Finish .005 max	1/10	
Hastelloy Alloy X							
Incoloy Alloy 804							
Incoloy Alloy 825							
Inconel Alloy 600							
Inconel Alloy 601							
Refractaloy 26							
Udimet 630	240 to 310	Cold Drawn or Aged	3000 to 3500	50 to 100	Rough .001	1/5	A60JV
					Finish .0002 max	1/10	

See section 16 for Cutting Fluid Recommendations.

*Wheel recommendations are for wet grinding of 2- to 4-inch (50 to 100 mm) diameter work. For DRY grinding—use a softer grade wheel. For LARGER diameter work—use a softer and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Wheel recommendations also apply to plunge grinding applications. Also see section 20.2, Grinding Guidelines.

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
Nickel Base, Wrought TD-Nickel††† TD-Ni-Cr†††	180 to 200	As Rolled	5500 to 6500	50 to 100	Rough .002 Finish 0005 max	1/2 1/6	A60JV
			28 to 33	15 to 30	Rough: .050 Finish: .013 max.	1/2 1/6	A60JV
Nickel Base, Cast B-1900 GMR-235 GMR-235D Hastelloy Alloy B Hastelloy Alloy C Hastelloy Alloy D IN-100 (Rene 100) IN-738 IN-792 Inconel Alloy 713C Inconel Alloy 718 M252 MAR-M200 MAR-M246 MAR-M421 MAR-M432 Rene 80 Rene 125 SEL SEL 15 TRW VI A Udimet 500 Udimet 700 ASTM A296 Grades CW-12M, N-12M, CY-40 ASTM A297 Grades HW, HX ASTM A494 Grades N-12M-1, N-12M-2, CY-40, CW-12M 1, CW-12M-2 ASTM A608 Grades HW50, HX40	200 to 425	As Cast or Cast and Aged	3000 to 3500	50 to 100	Rough 001 Finish 0002 max	1/5 1/10	A60JV
			15 to 18	15 to 30	Rough: .025 Finish: .005 max.	1/5 1/10	A60JV
Cobalt Base, Wrought AiResist 213 Haynes Alloy 25 (L605) Haynes Alloy 188 J-1570 MAR-M509 MAR-M918 S-816 V-36	180 to 240	Solution Treated	3000 to 3500	50 to 100	Rough: .001 Finish: .0002 max	1/5 1/10	A60JV
			15 to 18	15 to 30	Rough: .025 Finish: .005 max.	1/5 1/10	A60JV
	270 to 320	Solution Treated and Aged	3000 to 3500	50 to 100	Rough: .001 Finish: 0002 max	1/5 1/10	A60JV
			Up to 15	15 to 30	Rough: .025 Finish: .005 max.	1/5 1/10	A60JV

See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding of 2- to 4-inch (50 to 100 mm) diameter work. For DRY grinding—use a softer grade wheel. For LARGER diameter work—use a softer and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Wheel recommendations also apply to plunge grinding applications. Also see section 20.2, Grinding Guidelines.

††CAUTION: Toxic ... rial, refer to National Institute f ... Occupational Safety and Hea ... (NIOSH) for Precautions.

8.5 Cylindrical Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
39. HIGH TEMPERATURE ALLOYS, WROUGHT AND CAST (cont.)							
Cobalt Base, Cast							
AiResist 13	220 to 290	As Cast or Cast and Aged	3000 to 3500	50 to 100	Rough .001	1/5	A60JV
AiResist 215					Finish .0002 max	1/10	
FSX-414			15 to 18	15 to 30	Rough: .025	1/5	A60JV
HS-6					Finish: .005 max.	1/10	
HS-21							
HS-31 (X-40)							
HOWMET #3							
MAR-M302	290 to 425	As Cast or Cast and Aged	3000 to 3500	50 to 100	Rough: .001	1/5	A60JV
MAR-M322					Finish: .0002 max	1/10	
MAR-M509			15 to 18	15 to 30	Rough: .025	1/5	A60JV
NASA Co-W-Re					Finish: .005 max.	1/10	
WI-52							
X-45							
Iron Base, Wrought							
A-286	180 to 230	Solution Treated	3000 to 4000	50 to 100	Rough: .001	1/5	A60JV
Discaloy					Finish: .0002 max	1/10	
Inco'oy Alloy 800			15 to 20	15 to 30	Rough .025	1/5	A60JV
Incoloy Alloy 800H					Finish: .005 max.	1/10	
Incoloy Alloy 801							
Incoloy Alloy 802							
N-155							
V-57							
W-545							
16-25-6							
19-9DL	250 to 320	Solution Treated and Aged	3000 to 4000	50 to 100	Rough: .001	1/5	A60JV
					Finish: .0002 max.	1/10	
			15 to 20	15 to 30	Rough: .025	1/5	A60JV
					Finish: .005 max.	1/10	
4C. REFRACTORY ALLOYS, WROUGHT, CAST, P/M**							
Columbium †† ‡‡**							
C103	170 to 225	Stress Relieved	4000	50 to 100	Rough, .001	1/5	A60KV
C129Y					Finish .0003 max.	1/10	
Cb-1Zr			20	15 to 30	Rough: .025	1/5	A60KV
Cb-752					Finish: .005 max.	1/10	
FS-85							
FS-291							
WC-3015							

See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding of 2- to 4-inch [50 to 100 mm] diameter work. For DRY grinding—use a softer grade wheel. For LARGER diameter work—use a softer and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Wheel recommendations also apply to plunge grinding applications. Also see section 20.2, Grinding Guidelines.

**Due to the brittleness of refractory alloys, cracking, chipping, flaking and breakout tend to occur, particularly on the edges of the machined surfaces.

††CAUTION: Toxic Material; refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions.

‡‡CAUTION: Potential Fire Hazard. Exercise caution in grinding and disposing of swarf.

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
Molybdenum** Mo, Mo-50Re, TZC, TZM	220 to 290	Stress Relieved	4000	50 to 100	Rough .001	1/5	A60LV
					Finish .0003 max	1/10	
			20	15 to 30	Rough: .025	1/5	A60LV
					Finish: .008 max.	1/10	
Tantalum** ASTAR 811C, T-111, T-222, Ta-10W, Ta-Hf, Ta63	200 to 250	Stress Relieved	4000	50 to 100	Rough .001	1/5	A60KV
					Finish. .0003 max	1/10	
			20	15 to 30	Rough: .025	1/5	A60KV
					Finish: .008 max.	1/10	
Tungsten** 85% density, 93% density, 96% density, 100% density	180 to 320	Pressed and Sintered, Forged, or Arc Cast	2000	50 to 100	Rough .001	1/5	C60KV
					Finish .0003 max.	1/10	
			10	15 to 30	Rough: .025	1/5	C60KV
					Finish: .008 max.	1/10	
Tungsten - 2 Thoria** ††	260 to 320	Pressed and Sintered	2000	50 to 100	Rough: .001	1/5	C60KV
					Finish .0003 max	1/10	
			10	15 to 30	Rough: .025	1/5	C60KV
					Finish: .008 max.	1/10	
Tungsten Alloys** GE-218, W-15Mo, W-5Re, W-25Re, W-25Re-30Mo	260 to 320	As Cast	2000	50 to 100	Rough: .001	1/5	C60KV
					Finish: .0003 max.	1/10	
			10	15 to 30	Rough: .025	1/5	C60KV
					Finish .008 max.	1/10	
Tungsten Alloys** Gyromet, Mallory 2000, W-10Ag, W-7Ni-4Cu	290 to 320	Pressed and Sintered	2000	50 to 100	Rough: .001	1/5	C60KV
					Finish .0003 max	1/10	
			10	15 to 30	Rough: .025	1/5	C60KV
					Finish .008 max.	1/10	

See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding of 2- to 4-inch (50 to 100 mm) diameter work. For DRY grinding—use a softer grade wheel. For LARGER diameter work—use a softer and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Wheel recommendations also apply to plunge grinding applications. Also see section 20.2, Grinding Guidelines.

**Due to the brittleness of refractory alloys, cracking, chipping, flaking and breakout tend to occur, particularly on the edges of the machined surfaces.

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8.5 Cylindrical Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
40. REFRACTORY ALLOYS, WROUGHT, CAST, P/M (cont.)**							
Tungsten Alloys**							
Anviloy 1100	290	Pressed	2000	50	Rough	1/5	C60KV
Anviloy 1150	to	and		to	.001		
Anviloy 1200	320	Sintered		100	Finish .0003 max	1/10	
			10	15	Rough: .025	1/5	C60KV
				to			
				30	Finish: .008 max	1/10	
44. URANIUM, WROUGHT†† ‡‡							
	56 R_A		3000	40	Rough .002	1/5	C46HV
	to	Annealed	to	to			
	58 R_A		5000	60	Finish .0005 max	1/10	
			15	12	Rough: .050	1/5	C46HV
			to	to			
			25	18	Finish: .013 max	1/10	
45. ZIRCONIUM ALLOYS, WROUGHT‡‡							
Zr-2%Hf (Grade 11)				60	Rough: .001	1/6	C60KV or CA60PB
Zr-0.001%Hf (Grade 21)			3000	to			
Zircaloy 2 (Grade 32)	140	Rolled, Extruded		100	Finish .0005 max	1/12	
Zircaloy 4 (Grade 34)	to	or Forged					
	280			18	Rough: .025	1/6	C60KV or CA60PB
			16	to			
				30	Finish: .013 max	1/12	
47 POWDER METAL ALLOYS§§							
Copper§§					Rough. .002	1/3	C46JV
			5500	70			
			to	to			
	50 R_F		6500	100	Finish .0005 max	1/6	
	to	As Sintered					
	70 R_F						
			28	21	Rough: .050	1/3	C46JV
			to	to			
			38	30	Finish: .013 max	1/6	
Brasses§§					Rough. .002	1/3	C46KV
CZP-0218-T			5500	70			
CZP-0218-U			to	to			
CZP-0218-W	35 R_H		6500	100	Finish 0005 max.	1/6	
90Cu-10Zn	to	As Sintered					
90Cu-10Zn-0.5Pb	81 R_H						
70Cu-30Zn							
68.5Cu-30Zn-1.5Pb			28	21	Rough: .050	1/3	C46KV
			to	to			
			38	30	Finish: .013 max	1/6	
Bronzes§§					Rough .002	1/3	C46KV
CT-0010-N			5500	70			
CT-0010-R			to	to			
CT-0010-S	30 R_F		6500	100	Finish 0005 max	1/6	
95Cu-5Al	to	As Sintered					
77Cu-15Pb-7Sn-1Fe-1C	75 R_F						
			[illegible]	[illegible]	[illegible]	1/3	C46KV
			[illegible]	[illegible]	[illegible]	1/6	

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**Due to the brittleness of refractory alloys, cracking, chipping, flaking and breakout tend to occur, particularly on the edges of the machined surfaces.

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‡‡CAUTION: Potential Fire Hazard—exercise caution in grinding and disposing of swarf.

§§Grinding of low-density parts is not recommended because surface porosity will be reduced or lost.

MATERIAL	HARD-NESS Bnn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
Copper-Nickel Alloys§§ CZN 1818-T CZN-1818-U CZN-1818-W CZNP-1618-U CZNP-1618-W 90Cu-10Ni 62Cu-18Ni-18Zn-2Sn	22 R_B to 100 R_B	As Sintered	5500 to 6500	70 to 100	Rough 002 Finish 0005 max	1/3 1/6	C46KV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max	1/3 1/6	C46KV
Nickel§§	45 R_B	As Sintered	5500 to 6500	50 to 100	Rough 002 Finish 0005 max	1/5 1/10	A60JV
			28 to 33	15 to 30	Rough: .050 Finish: .013 max	1/5 1/10	A60JV
Nickel Alloys§§ 67Ni-30Cu-3Fe	34 R_B to 50 R_B	As Sintered	5500 to 6500	50 to 100	Rough 002 Finish 0005 max	1/5 1/10	C60IV
			28 to 33	15 to 30	Rough: .050 Finish: .013 max	1/5 1/10	C60IV
Refractory Metal Base§§ 87W-13Cu 85W-15Ag 74W-26Cu 72.5W-27.5Ag 65W-35Ag 56W + C-44Cu 55W-45Cu 51W-49Ag 50W + C-50Ag	101 to 260	As Sintered	2000	50 to 100	Rough 001 Finish 0003 max	1/5 1/10	C60KV
			10	15 to 30	Rough: .025 Finish: .008 max	1/5 1/10	C60KV
Refractory Metal Base§§ 61Mo-39Ag 50Mo-50Ag	75 R_B to 82 R_B	As Sintered	4000	50 to 100	Rough: 001 Finish .0003 max	1/5 1/10	A60LV
			23	15 to 30	Rough: .025 Finish: .008 max	1/5 1/10	A60LV

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8.5 Cylindrical Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
47. POWDER METAL ALLOYS§§(cont.)							
Irons§§							
F-0000-N			5500	70	Rough:	1/2	
F-0000-P			to	to	.002		C46KV
F-0000-R	50		6500	100			
F-0000-S	to				Finish:	1/6	
F-0000-T	67	As Sintered			.001 max		
	500kg		28	21	Rough: .050	1/2	
			to	to			C46KV
			33	30	Finish: .025 max.	1/6	
Steels§§							
F-0008-P			5500	70	Rough:	1/2	
F-0008-S			to	to	.002		A60MV
F-0005-S			6500	100			
FC-0205-S	101	As Sintered			Finish:	1/6	
FC-0208-P	to	or			.0005 max.		
FC-0208-S	426	Heat Treated	28	21	Rough: .050	1/2	
FC-0508-P			to	to			A60MV
FC-1000-N			33	30	Finish: .013 max.	1/6	
FN-0205-S							
FN-0205-T							
FN-0405-R							
FN-0405-S							
FN-0405-T							
FX-1005-T							
FX-2008-T							
Stainless Steels§§							
SS-303-R			5500	50	Rough:	1/2	
SS-304-R			to	to	.002		C54JV
SS-316-R			6500	100			
SS-410-R	107	As Sintered			Finish:	1/6	
	to	or			.0005 max		
	285	Heat Treated	28	15	Rough: .050	1/2	
			to	to			C54JV
			33	30	Finish: .013 max.	1/6	
Aluminum Alloys§§							
90 5Al-5Sn-4Cu			5500	50	Rough:	1/2	
88Al-5Sn-4Pb-3Cu			to	to	.002		C54JV†
Al-1Mg-0.6Si-0 25Cu	55 R_H		6500	150			
Al-0 6Mg-0 4Si	to	Solution Treated			Finish:	1/6	
Al 4 4Cu-0 8Si-0 4Mg	98 R_H	and Aged			.0005 max.		
			28	15	Rough: .050	1/2	
			to	to			C54JV†
			33	46	Finish: .013 max.	1/6	
48. MACHINABLE CARBIDES							
Ferro-Tic			4000	40	Pough:	1/6	
			to	to	.001		A60HV
	40 R_C		6000	60			
	to	Annealed			Finish:	1/12	
	51 R_C				.0003 max		
			20	12	Rough: .025	1/6	
			to	to			A60HV
			30	16	Finish: .006 max.	1/12	

See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding of 2- to 4-inch [50 to 100 mm] diameter work For DRY grinding—use a softer grade wheel For LARGER diameter work—use a softer and/or coarser grit wheel For SMALLER diameter work—use a harder grade wheel Wheel recommendations also apply to plunge grinding applications Also see section 20 2, Grinding Guidelines

† Wax filled

§§ Grinding of low-density parts is not recommended , because surface porosity will be reduced or lost

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in pass mm/pass	TRAVERSE Wheel width per rev of work	WHEEL IDENTIFI-CATION* ANSI ISO
48. MACHINABLE CARBIDES (cont.) (materials listed on preceding page)	68 R_C to 70 R_C	Hardened and Tempered	4000 to 6000	40 to 60	Rough .001 Finish .0003 max	1/6 1/12	A60HV‡
			20 to 30	12 to 18	Rough: .025 Finish: .008 max.	1/6 1/32	A60HV‡
49 CARBIDES Titanium Carbide Tungsten Carbide	89 R_A to 94 R_A	—	5500 to 6500	50 to 60	Rough .001 Finish .0003 max	1/5 1/10	Rough C60JV Finish C120IVi
			28 to 33	15 to 18	Rough: .025 Finish: .008 max.	1/5 1/10	Rough: C60JV Finish: C120IV‡
50 FREE MACHINING MAGNETIC ALLOYS Magnetic Core Iron-FM (up to 2.5% Si)	185 to 240	Wrought	5500 to 6500	70 to 100	Rough .002 Finish .001 max.	1/2 1/6	A46KV
			28 to 33	21 to 30	Rough: .050 Finish: .025 max.	1/2 1/6	A46KV
Hi Perm 49-FM	185 to 240	Wrought	5500 to 6500	50 to 100	Rough .002 Finish .0005 max	1/5 1/10	C54KV
			28 to 33	15 to 30	Rough: .050 Finish: .013 max.	1/5 1/10	C54KV
51. MAGNETIC ALLOYS Magnetic Core Iron (up to 4% Si)	185 to 240	Wrought	5500 to 6500	70 to 100	Rough .002 Finish .001 max	1/2 1/6	A46KV
			28 to 33	21 to 30	Rough: .050 Finish: .025 max.	1/2 1/6	A46KV
Hi Perm 49 HyMu 80	185 to 240	Wrought	5500 to 6500	50 to 100	Rough: .002 Finish .0005 max.	1/5 1/10	C54KV
			28 to 33	15 to 30	Rough: .050 Finish: .013 max.	1/6 1/10	C54KV

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‡Diamond wheel is preferable, see section 8.7

8.5 Cylindrical Grinding

MATERIAL	HARD-NESS Bnn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
51. MAGNETIC ALLOYS (cont.)							
Alnico Alnico II Alnico III Alnico IV Alnico V Alnico V-7 Alnico XII Columax-5 Hyflux Alnico V-7	45 R_C to 58 R_C	As Cast	5500 to 6500	50 to 75	Rough .002 Finish .0005 max	1/5 1/10	A60JV
			28 to 33	15 to 23	Rough .050 Finish .013 max.	1/5 1/10	A60JV
52. FREE MACHINING CONTROLLED EXPANSION ALLOYS Invar 36	125 to 220	Annealed or Cold Drawn	5500 to 6500	50 to 100	Rough .002 Finish .0005 max	1/5 1/10	C54KV
			28 to 33	15 to 30	Rough .050 Finish .013 max.	1/5 1/10	C54KV
53. CONTROLLED EXPANSION ALLOYS Invar Kovar	125 to 250	Annealed or Cold Drawn	5500 to 6500	50 to 100	Rough .002 Finish .0005 max	1/5 1/10	C54KV
			28 to 33	15 to 30	Rough .050 Finish .013 max.	1/5 1/10	C54KV
54. CARBONS & GRAPHITES Mechanical Grades	40 to 100 Shore	Molded or Extruded	5500 to 6500	50 to 75	Rough .002 Finish .0005 max	1/2 1/6	C36LV
			28 to 33	15 to 23	Rough .050 Finish .013 max.	1/2 1/6	C36LV
Brush Grade Carbon	8 to 90 Shore	Molded or Extruded	5500 to 6500	50 to 75	Rough .002 Finish .0005 max	1/2 1/6	C36LV
			28 to 33	15 to 23	Rough .050 Finish .013 max.	1/2 1/6	C36LV

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MATERIAL	HARD-NESS Bnn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
Graphite	—	—	5000 to 6500	50 to 75	Rough .002 Finish .0005 max	1/2 1/6	Rough C36JV Finish C60JV
			25 to 33	15 to 23	Rough: .050 Finish: .013 max.	1/2 1/6	Rough: C36JV Finish: C60JV
55. GLASSES & CERAMICS Glass	480 to 530 Knoop 100g	—	5500 to 6500	70 to 100	Rough .001 Finish .0005 max	1/5 1/10	Rough C80GV Finish A180KV
			28 to 33	21 to 30	Rough: .025 Finish: .013 max.	1/5 1/10	Rough: C80GV Finish: A160KV
Porcelain Enamel	—	—	5500 to 6500	70 to 100	Rough .001 Finish .0005 max	1/5 1/10	C70KV
			28 to 33	21 to 30	Rough .025 Finish: .013 max.	1/5 1/10	C70KV
Ceramics Alumina (Aluminum Oxide) Alumina-Mullite Aluminum Silicate Beryllia (Beryllium Oxide)†† Magnesia (Magnesium Oxide) Mullite Silicon Carbide Silicon Nitride Thoria (Thorium Oxide)†† Titania (Titanium Oxide) Titanium Diboride†† Zircon (Zirconium Silicate) Zirconia (Zirconium Oxide)	Over 800 Knoop	Fired	5500 to 6500	70 to 100	Rough .001 Finish .0002 max.	1/5 1/10	Rough: C46KV† Finish C80KV†
			28 to 33	21 to 30	Rough .025 Finish: .005 max.	1/5 1/10	Rough: C46KV† Finish: C80KV†
56. PLASTICS **Thermoplastics**	—	Cast, Molded, Extruded, or Filled and Molded	5500 to 6500	70 to 100	Rough .005 Finish .0005 max	1/3 1/6	C60KV
			28 to 33	21 to 30	Rough .13 Finish: .013 max.	1/3 1/6	C60KV

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†Diamond wheel is preferable, see section 8.7.

††CAUTION: Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions.

8.5 Cylindrical Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
56. PLASTICS (cont.)							
Thermosetting Plastics	—	Cast	5500 to 6500	70 to 100	Rough: .005 Finish: .0005 max	1/3 1/6	C46IV
			28 to 33	21 to 30	Rough: .13 Finish: .013 max	1/3 1/6	C46IV
	—	Molded	5500 to 6500	70 to 100	Rough: .005 Finish: .0005 max	1/3 1/6	C46KV
			28 to 33	21 to 30	Rough: .13 Finish: .013 max	1/3 1/6	C46KV
	—	Laminated	5500 to 6500	70 to 100	Rough: .005 Finish: .0005 max	1/3 1/6	C36LV
			28 to 33	21 to 30	Rough: .13 Finish: .013 max	1/3 1/6	C36LV
58. FLAME (THERMAL) SPRAYED MATERIALS							
Sprayed Carbides	—	—	5500 to 6500	70 to 100	Rough: .001 Finish: .0005 max	1/4-1/2 1/12-1/6	C80FV§
Chromium Carbide							
Chromium Carbide-Cobalt Blend							
Columbium Carbide							
Tantalum Carbide							
Titanium Carbide							
Tungsten Carbide							
Tungsten Carbide-Cobalt							
Tungsten Carbide (Cobalt)-Nickel Alloy Blend			28 to 33	21 to 30	Rough: .025 Finish: .013 max	1/4-1/2 1/12-1/6	C80FV§

See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding of 2- to 4-inch [50 to 100 mm] diameter work. For DRY grinding—use a softer grade wheel. For LARGER diameter work—use a softer and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Wheel recommendations also apply to plunge grinding applications. Also see section 20.2 Grinding Guidelines.

§Diamond wheel is preferable for flame sprayed carbides and ceramics see section 8.7

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
Inorganic Coating Materials Alumina (Pure) Alumina (Grey) containing Titania Alumina Nickel-Aluminide Blends Barium Titanate Boron†† Calcium Titanate Calcium Zirconate Chromium Disilicide†† Chromium Oxide†† Cobalt (40%) Zirconia Blend Columbium (Niobium)†† Glass (Kovar sealing)†† Hexaboron Silicide†† Magnesia Alumina Spinel Magnesium Zirconate Molybdenum Disilicide Mullite Nickel (40%), Alumina Blend Nickel Oxide Rare Earth Oxides Tantalum Titania (50%), Alumina Blend Titanium Oxide Tungsten Yttrium Zirconate Zirconia (Lime Stabilized) Zirconia, Nickel-Aluminide Blends Zirconium Oxide (Hafnia Free, Lime Stabilized) Zirconium Silicate	—	—	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough .001 Finish 0005 max Rough: .025 Finish: .013 max.	1/4-1/2 1/12-1/6 1/4-1/2 1/12-1/6	C100GVS C100GVS
Sprayed Metals (Group I) Co-Cr-B Alloy (Self Fluxing) Ni-Cr-B Alloy (Self Fluxing) Nickel Chrome Steel (Special) Stainless Steel	—	—	5500 to 6500 28 to 33	70 to 100 21 to 30	Rough: .001 Finish: 0005 max Rough: .025 Finish: .013 max.	1/4-1/2 1/12-1/6 1/4-1/2 1/12-1/6	C60JV C60JV
Sprayed Metals (Group II) Bronze Chromium Cobalt Nickel Molybdenum Monel	—	—	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .001 Finish: .0005 max. Rough: .025 Finish: .013 max.	1/4-1/2 1/12-1/6 1/4-1/2 1/12-1/6	C60JV C60JV
Sprayed Metals (Group III) Carbon Steel Iron Precipitation Hardening Steel	—	—	5500 to 6500 28 to 33	50 to 100 15 to 30	Rough: .001 Finish: 0005 max Rough: .025 Finish: .013 max.	1/4-1/2 1/12-1/6 1/4-1/2 1/12-1/6	C46KV C46KV

See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding of 2- to 4-inch [50 to 100 mm] diameter work. For DRY grinding—use a softer grade wheel. For LARGER diameter work—use a softer and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Wheel recommendations also apply to plunge grinding applications. Also see section 20.2, Grinding Guidelines.

§Diamond wheel is preferable for flame sprayed carbides and ceramics, see section 8.7

††CAUTION: Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions

8.5 Cylindrical Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
59. PLATED MATERIALS Chromium Plate	—	—	3000 to 4000	70 to 100	Rough: .002 Finish: .0004 max.	1/4 1/8	A80IV† A120IV‡
			15 to 20	21 to 30	Rough: .050 Finish: .010 max.	1/4 1/8	A80IV† A120IV‡
Nickel Plate Silver Plate	—	—	5500 to 6500	70 to 100	Rough: .002 Finish: .0005 max	1/5 1/10	A60KV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/5 1/10	A60KV
60. PRECIOUS METALS Silver	—	—	5500 to 6500	70 to 100	Rough: .002 Finish: .0005 max.	1/5 1/10	A100JV
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/5 1/10	A100JV
61. RUBBER	Soft	—	5500 to 6500	70 to 150	Rough: .005 Finish: .001 max.	1/2 1/6	C30JB
			28 to 33	21 to 46	Rough: .13 Finish: .025 max.	1/2 1/6	C30JB
	Hard	—	5500 to 6500	70 to 150	Rough: .005 Finish: .001 max.	1/2 1/6	C36KB
			28 to 33	21 to 46	Rough: .13 Finish: .025 max.	1/2 1/6	C36KB

See section 16 for Cutting Fluid Recommendations.

*Wheel recommendations are for wet grinding of 2- to 4-inch (50 to 100 mm) diameter work. For DRY grinding—use a softer grade wheel For LARGER diameter work—use a softer and/or coarser grit wheel For SMALLER diameter work—use a harder grade wheel Wheel recommendations also apply to plunge grinding applications Also see section 20 2, Grinding Guidelines

†For commercial finish

‡For high finish

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION ANSI ANSI
1. FREE MACHINING CARBON STEELS, WROUGHT **Low Carbon Resulfurized** 1108 1118 1109 1119 1110 1211 1115 1212 1116 1213 1117 1215 **Medium Carbon Resulfurized** 1132 1140 1145 1137 1141 1146 1139 1144 1151 **Low Carbon Leaded** 10L18 12L13 12L15 11L17 12L14 **Medium Carbon Leaded** 10L45 11L37 11L44 10L50 11L41	Over 50 R_C	Carburized and/or Quenched and Tempered	5000 to 7500 25 to 38	50 to 100 15 to 30	Rough 001 Finish 0002 max Rough: 025 Finish: .005 max.	1/4 1/8 1/4 1/8	B100T100B B100T100B
2. CARBON STEELS, WROUGHT **Low Carbon** 1005 1012 1019 1026 1006 1013 1020 1029 1008 1015 1021 1513 1009 1016 1022 1518 1010 1017 1023 1522 1011 1018 1025 **Medium Carbon** 1030 1042 1053 1541 1033 1043 1055 1547 1035 1044 1524 1548 1037 1045 1525 1551 1038 1046 1526 1552 1039 1049 1527 1040 1050 1536 **High Carbon** 1060 1074 1085 1566 1064 1075 1086 1572 1065 1078 1090 1069 1080 1095 1070 1084 1561	Over 50 R_C	Carburized and/or Quenched and Tempered	5000 to 7500 25 to 38	50 to 100 15 to 30	Rough 001 Finish. 0002 max. Rough: 025 Finish: .005 max.	1/4 1/8 1/4 1/8	B100T100B B100T100B

See section 16 for Cutting Fluid Recommendations
See section 20.1 for additional information.

8.6 Cylindrical Grinding

Cubic Boron Nitride Wheels

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION ANSI ANSI
4. FREE MACHINING ALLOY STEELS, WROUGHT **Medium Carbon Resulfurized** 4140 4140Se 4142Te 4145Se 4147Te 4150 **Medium and High Carbon Leaded** 41L30 41L47 51L32 86L40 41L40 41L50 52L100 41L45 43L40 86L20	Over 50 R_C	Carburized and/or Quenched and Tempered	5000 to 7500	50 to 100	Rough: .001 Finish: .0002 max	1/4 1/8	B100T100B
			25 to 38	15 to 30	Rough: .025 Finish: .005 max.	1/4 1/8	B100T100B
5. ALLOY STEELS, WROUGHT **Low Carbon** 4012 4615 4817 8617 4023 4617 4820 8620 4024 4620 5015 8622 4118 4621 5115 8822 4320 4718 5120 9310 4419 4720 6118 94B15 4422 4815 8115 94B17 **Medium Carbon** 1330 4145 5132 8640 1335 4147 5135 8642 1340 4150 5140 8645 1345 4161 5145 86B45 4027 4340 5147 8650 4028 4427 5150 8655 4032 4626 5155 8660 4037 50B40 5160 8740 4042 50B44 51B60 8742 4047 5046 6150 9254 4130 50B46 81B45 9255 4135 50B50 8625 9260 4137 5060 8627 94B30 4140 50B60 8630 4142 5130 8637 **High Carbon** 50100 51100 52100 M-50	Over 50 R_C	Carburized and/or Quenched and Tempered	5000 to 7500	50 to 100	Rough .001 Finish .0002 max	1/4 1/8	B100T100B
			25 to 38	15 to 30	Rough: .025 Finish: .005 max.	1/4 1/8	B100T100B
6. HIGH STRENGTH STEELS, WROUGHT 300M H11 4330V H13 4340 HP 9-4-20 4340Si HP 9-4-25 98BV40 HP 9-4-30 D6ac HP 9-4-45	Over 50 R_C	Quenched and Tempered	5000 to 7500	50 to 100	Rough: .001 Finish: 0002 max	1/4 1/8	B100T100B
			25 to 38	15 to 30	Rough: .025 Finish: .005 max.	1/4 1/8	B100T100B

See section 16 for Cutting Fluid Recommendations
See section 20.1 for additional information

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION ANSI ANSI
7. MARAGING STEELS, WROUGHT 120 Grade 300 Grade 180 Grade 350 Grade 200 Grade HY230 250 Grade ASTM A538 Grades A, B C	Over 50 R_C	Maraged	5000 to 7500	50 to 100	Rough: 001 Finish 0002 max	1/4 1/8	B100T100B
			25 to 38	15 to 30	Rough: 025 Finish: 005 max.	1/4 1/8	B100T100B
8. TOOL STEELS, WROUGHT A2 H14 M10 P20 A3 H19 M30 P21 A4 H21 M33 S1 A6 H22 M34 S2 A7 H23 M36 S5 A8 H24 M41 S6 A9 H25 M42 S7 A10 H26 M43 T1 D2 H42 M44 T2 D3 L2 M46 T4 D4 L6 M47 T5 D5 L7 O1 T6 D7 M1 O2 T8 F1 M2 O6 T15 F2 M3-1 O7 W1 H10 M3-2 P2 W2 H11 M4 P4 W5 H12 M6 P5 H13 M7 P6 SAE J438b, Types W108, W109, W110, W112, W209, W210, W310	Over 50 R_C	Quenched and Tempered	5000 to 7500	50 to 100	Rough: .001 Finish .0002 max.	1/4 1/8	B100T100B
			25 to 38	15 to 30	Rough: .025 Finish: .005 max.	1/4 1/8	B100T100B
9. NITRIDING STEELS, WROUGHT Nitralloy 125 Nitralloy 230 Nitralloy 135 Nitralloy EZ Nitralloy 135 Mod Nitralloy N Nitralloy 225 Nitrex 1	60 R_C to 65 R_C	Nitrided	5000 to 7500	50 to 100	Rough .001 Finish .0002 max.	1/4 1/8	B100T100B
			25 to 38	15 to 30	Rough: .025 Finish: .005 max.	1/4 1/8	B100T100B
15. CARBON STEELS, CAST **Low Carbon** ASTM A426: Grade CP1 1010 1020 **Medium Carbon** ASTM A352 Grades LCA, LCB, LCC ASTM A356 Grade 1 1030 1040 1050	Over 50 R_C	Carburized and/or Quenched and Tempered	5000 to 7500	50 to 100	Rough: .001 Finish: .0002 max	1/4 1/8	B100T100B
			25 to 38	15 to 30	Rough: .025 Finish: .005 max.	1/4 1/8	B100T100B

See section 16 for Cutting Fluid Recommendations
See section 20.1 for additional information

8.6 Cylindrical Grinding
Cubic Boron Nitride Wheels

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION ANSI ANSI
16. ALLOY STEELS, CAST **Low Carbon** ASTM A217 Grade WC9 ASTM A352 Grades LC3 LC4 ASTM A426 Grades CP2, CP5, CP5b, CP11, CP12, CP15, CP21, CP22 1320 4110 8020 2315 4120 8620 2320 4320 **Medium Carbon** ASTM A27 Grades N1, N2, U-60-30, 60-30, 65-35, 70-36, 70-40 ASTM A148 Grades 80-40, 80-50, 90-60, 105-85, 120-95, 150-125, 175-145 ASTM A216 Grades WCA, WCB, WCC ASTM A217 Grades WC1, WC4, WC5, WC6 ASTM A352 Grades LC1, LC2, LC2-1 ASTM A356 Grades 2, 5, 6, 8, 9, 10 ASTM A389, Grades C23, C24 ASTM A486, Classes 70, 90, 120 ASTM A487 Classes 1N, 2N, 4N, 6N, 8N, 9N, 10N, DN, 1Q 2Q, 4Q, 4QA, 6Q, 7Q, 8Q 9Q, 10Q 1330 4130 80B30 8640 1340 4140 8040 9525 2325 4330 8430 9530 2330 4340 8440 9535 4125 8030 8630	Over 50 R_C	Carburized and/or Quenched and Tempered	5000 to 7500 25 to 38	50 to 100 15 to 30	Rough .001 Finish 0002 max Rough: .025 Finish: .005 max.	1/4 1/8 1/4 1/8	B100T100B B100T100B
17. TOOL STEELS, CAST ASTM A597 Grades CA-2, CD-2, CD-5, CH-12, CH-13, CO-1, CS-5	Over 50 R_C	Quenched and Tempered	5000 to 7500 25 to 38	50 to 100 15 to 30	Rough: 001 Finish, .0002 max. Rough: .025 Finish: .005 max.	1/4 1/8 1/4 1/8	B100T100B B100T100B

See section 16 for Cutting Fluid Recommendations
See section 20 1 for additional information

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION ANSI ANSI
48. MACHINABLE CARBIDES Ferro-Tic	68 R_C to 72 R_C	Hardened and Tempered	5500 to 6500	40 to 50	Rough: .001 Finish: 0002 max.	1/5 1/10	D100-L100-B-1/8
			28 to 33	12 to 15	Rough: .025 Finish: .005 max.	1/5 1/10	D100-L100-B-1/8
49. CARBIDES Titanium Carbide Tungsten Carbide	89 R_A to 94 R_A	—	5500 to 6500	50 to 60	Rough. .002 Finish. .0002 max.	1/5 1/10	D120-R100-B-1/8 D320-h75-B-1/8
			28 to 33	15 to 18	Rough: .050 Finish: .005 max.	1/5 1/10	D120-R100-B-1/8 D320-h75-B-1/8
51. MAGNETIC ALLOYS Magnetic Core Iron (up to 4% Si) Hi Perm 49 HyMu 80	185 to 240	Wrought	5500 to 6500	50 to 60	Rough: .005 Finish: .001 max	1/4 1/8	D120-N75-M-1/8 D220-N75-M-1/8
			28 to 33	15 to 18	Rough: .13 Finish: .025 max.	1/4 1/8	D120-N75-M-1/8 D220-N75-M-1/8
Alnico I Alnico II Alnico III Alnico IV Alnico V Alnico V-7 Alnico XII Columax-5 Hyflux Alnico V-7	45 R_C to 58 R_C	As Cast	5500 to 6500	40 to 50	Rough: .002 Finish: .0005 max.	1/6 1/12	D120-N75-M-1/8 D220-N75-M-1/8
			28 to 33	12 to 15	Rough: .050 Finish: .013 max.	1/6 1/12	D120-N75-M-1/8 D220-N75-M-1/8
54. CARBONS & GRAPHITES Mechanical Grades Brush Grade Carbon	8 to 100 Shore	Molded or Extruded	5500 to 6500	50 to 60	Rough: .005 Finish .001 max.	1/6 1/12	D60E* D220E*
			28 to 33	15 to 18	Rough: .13 Finish: .025 max.	1/6 1/12	D60E* D220E*
Graphite	—	—	5500 to 6500	30 to 40	Rough: .003 Finish: .001 max.	1/5 1/10	D60E* D220E*
			28 to 33	9 to 12	Rough: .08 Finish: .025 max.	1/5 1/10	D60E* D220E*

See section 16 for Cutting Fluid Recommendations
See section 20.1 for additional information

*Electroplated.

8.7 Cylindrical Grinding
Diamond Wheels

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION ANSI ANSI
55. GLASSES & CERAMICS							
Machinable Glass-Ceramic (MACOR)	250 Knoop 100g	Cast	5500 to 6500	30 to 60	Rough .005	1/4	D100-N100-M-1/8
					Finish, .001 max.	1/8	D220-N100-M-1/8
			28 to 33	15 to 13	Rough: .13	1/4	D100-N100-M-1/8
					Finish: .025 max.	1/8	D220-N100-M-1/8
PYROCERAM	700 Knoop 100g	—	5500 to 6500	20 to 40	Rough .002	1/5	D120-N75-M-1/8
					Finish .001 max.	1/10	D220-N75-M-1/8
			28 to 33	6 to 12	Rough: .050	1/5	D120-N75-M-1/8
					Finish: .025 max.	1/10	D220-N75-M-1/8
Glass	480 to 530 Knoop 100g	—	4500 to 6000	20 to 40	Rough: .002	1/6	D120-N75-M-1/8
					Finish .0005 max.	1/12	D220-N75-M-1/8
			23 to 30	6 to 12	Rough: .050	1/6	D120-N75-M-1/8
					Finish: .013 max.	1/12	D220-N75-M-1/8
Ceramics	Over 800 Knoop	Fired	5500 to 6500	30 to 40	Rough: .002	1/6	D120-N100-M-1/8
Alumina (Aluminum Oxide)					Finish: .0005 max	1/12	D220-N100-M-1/8
Alumina-Mullite							
Aluminum Silicate							
Beryllia (Beryllium Oxide)††							
Magnesia (Magnesium Oxide)							
Mullite							
Silicon Carbide							
Silicon Nitride							
Thoria (Thorium Oxide)††							
Titania (Titanium Oxide)							
Titanium Diboride††							
Zircon (Zirconium Silicate)							
Zirconia (Zirconium Oxide)			28 to 33	9 to 12	Rough: .050	1/6	D120-N100-M-1/8
					Finish: .013 max.	1/12	D220-N100-M-1/8
57. COMPOSITES							
Kevlar 49	—	—	4500 to 6500	75 to 150	Rough: .001	1/8	D100-N100-B-1/8
					Finish: .0005 max.	1/12	D600-N100-B-1/8
			29 to 39	23 to 46	Rough: .025	1/8	D100-N100-B-1/8
					Finish: .013 max.	1/12	D600-N100-B-1/8

See section 16 for Cutting Fluid Recommendations
See section 20.1 for additional information

†† CAUTION Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION ANSI ANSI
Graphite Epoxy	—	—	4500 to 6500	50 to 60	Rough: .002 Finish: .0005 max	1/8 1/12	D120-N100-B-1/8 D320-N100-B-1/8
			23 to 33	15 to 18	Rough: .050 Finish: .013 max.	1/8 1/12	D120-N100-B-1/8 D320-N100-B-1/8
Fiberglass Epoxy (E) Glass (S) Glass	—	—	3000 to 4000	50 to 60	Rough: .002 Finish: .0005 max	1/8 1/12	D80-M100-B-1/8 D120-N100-B-1/8
			15 to 20	15 to 18	Rough: .050 Finish: .013 max.	1/8 1/12	D80-M100-B-1/8 D120-N100-B-1/8
Boron Epoxy	—	—	5500 to 6500	50 to 60	Rough: .002 Finish: .0005 max.	1/8 1/12	D120-N100-B-1/8 D320-N100-B-1/8
			28 to 33	15 to 60	Rough: .050 Finish: .013 max.	1/8 1/12	D120-N100-B-1/8 D320-N100-B-1/8
58. FLAME (THERMAL) SPRAYED MATERIALS **Sprayed Carbides** Chromium Carbide Chromium Carbide-Cobalt Blend Columbium Carbide Tantalum Carbide Titanium Carbide Tungsten Carbide Tungsten Carbide-Cobalt Tungsten Carbide (Cobalt)-Nickel Alloy Blend	—	—	5500 to 6500	70 to 100	Rough: .002 Finish: .0005 max.	1/6 1/12	D120-N100-B-1/8 D220-N100-B-1/8
			28 to 33	21 to 30	Rough: .050 Finish: .013 max.	1/8 1/12	D120-N100-B-1/8 D220-N100-B-1/8

See section 16 for Cutting Fluid Recommendations
See section 20 1 for additional information

8.7 Cylindrical Grinding
Diamond Wheels

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION ANSI ANSI
58. FLAME (THERMAL) SPRAYED MATERIALS (cont.)							
Inorganic Coating Materials			5500 to 6500	70 to 100	Rough .002	1/6	D120-N100-B-1/8
Alumina (Pure)	—	—			Finish .0005 max.	1/12	D220-N100-B-1/8
Alumina (Grey) containing Titania			25 to 33	21 to 30	Rough .050	1/6	D120-N100-B-1/8
Alumina, Nickel-Aluminide Blends					Finish .013 max.	1/12	D220-N100-B-1/8
Barium Titanate							
Boron††							
Calcium Titanate							
Calcium Zirconate							
Chromium Disilicide††							
Chromium Oxide††							
Cobalt (40%), Zirconia Blend							
Columbium (Niobium)††							
Glass (Kovar sealing)††							
Hexaboron Silicide††							
Magnesia Alumina Spinel							
Magnesium Zirconate							
Molybdenum Disilicide							
Mullite							
Nickel (40%), Alumina Blend							
Nickel Oxide							
Rare Earth Oxides							
Tantalum							
Titania (50%), Alumina Blend							
Titanium Oxide							
Tungsten							
Yttrium Zirconate							
Zirconia (Lime Stabilized)							
Zirconia, Nickel-Aluminide Blends							
Zirconium Oxide (Hafnia Free, Lime Stabilized)							
Zirconium Silicate							

See section 16 for Cutting Fluid Recommendations
See section 20.1 for additional information.

†† CAUTION: Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
1. FREE MACHINING CARBON STEELS, WROUGHT **Low Carbon Resulfurized** 1108 1118 1109 1119 1110 1211 1115 1212 1116 1213 1117 1215 **Medium Carbon Resulfurized** 1132 1140 1145 1137 1141 1146 1139 1144 1151 **Low Carbon Leaded** 10L18 12L13 12L15 11L17 12L14 **Medium Carbon Leaded** 10L45 11L37 11L44 10L50 11L41	50 R_C max	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	5000 to 6500	75 to 200	Rough .0005 Finish .0002 max	1/3 1/6	A54MV
			25 to 33	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A54MV
	Over 50 R_C	Carburized and/or Quenched and Tempered	5000 to 6500	75 to 200	Rough .0005 Finish .0002 max	1/3 1/6	A60KV
			25 to 33	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A60KV
2. CARBON STEELS, WROUGHT **Low Carbon** 1005 1012 1019 1026 1006 1013 1020 1029 1008 1015 1021 1513 1009 1016 1022 1518 1010 1017 1023 1522 1011 1018 1025 **Medium Carbon** 1030 1042 1053 1541 1033 1043 1055 1547 1035 1044 1524 1548 1037 1045 1525 1551 1038 1046 1526 1552 1039 1049 1527 1040 1050 1536 **High Carbon** 1060 1074 1085 1566 1064 1075 1086 1572 1065 1078 1090 1069 1080 1095 1070 1084 1561	50 R_C max.	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	5000 to 6500	75 to 200	Rough: .0005 Finish: .0002 max.	1/3 1/6	A54MV
			25 to 33	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A54MV
	Over 50 R_C	Carburized and/or Quenched and Tempered	5000 to 6500	75 to 200	Rough: .0005 Finish. .0002 max.	1/3 1/6	A60KV
			25 to 33	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A60KV
3. CARBON AND FERRITIC ALLOY STEELS (HIGH TEMPERATURE SERVICE) ASTM A369: Grades FPA, FPB, FP1, FP2, FP3b, FP5, FP7, FP9, FP11, FP12, FP21, FP22	150 to 200	As Forged, Annealed or Normalized and Tempered	5000 to 6500	75 to 200	Rough: .0005 Finish: .0002 max.	1/3 1/6	A54MV
			25 to 33	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A54MV

Maximum hole length is 2.5 times hole diameter.
Maximum wheel width is 1.5 times wheel diameter
See section 16 for Cutting Fluid Recommendations.
*Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter holes. For LARGER holes—use the same or softer grade wheel. For SMALLER holes—use a harder grade wheel. Also see section 20.2, Grinding Guidelines.

8.8 Internal Grinding

MATERIAL	HARDNESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFICATION* ANSI ISO
4. FREE MACHINING ALLOY STEELS, WROUGHT **Medium Carbon Resulfurized** 4140 4140Se 4142Te 4145Se 4147Te 4150 **Medium and High Carbon Leaded** 41L30 41L47 51L32 86L40 41L40 41L50 52L100 41L45 43L40 86L20	50 R_C max	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	5000 to 6500	75 to 200	Rough 0005 Finish .0002 max	1/3 1/6	A60MV
			25 to 33	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A60MV
	Over 50 R_C	Carburized and/or Quenched and Tempered	5000 to 6500	75 to 200	Rough .0005 Finish .0002 max.	1/3 1/6	A60KV
			25 to 33	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A60KV
5. ALLOY STEELS, WROUGHT **Low Carbon** 4012 4615 4817 8617 4023 4617 4820 8620 4024 4620 5015 8622 4118 4621 5115 8822 4320 4718 5120 9310 4419 4720 6118 94B15 4422 4815 8115 94B17 **Medium Carbon** 1330 4145 5132 8640 1335 4147 5135 8642 1340 4150 5140 8645 1345 4161 5145 86B45 4027 4340 5147 8650 4028 4427 5150 8655 4032 4626 5155 8660 4037 50B40 5160 8740 4042 50B44 51B60 8742 4047 5046 6150 9254 4130 50B46 81B45 9255 4135 50B50 8625 9260 4137 5060 8627 94B30 4140 50B60 8630 4142 5130 8637 **High Carbon** 50100 51100 52100 M-50	50 R_C max.	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	5000 to 6500	75 to 200	Rough: .0005 Finish: .0002 max.	1/3 1/6	A60MV
			25 to 33	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A60MV
	Over 50 R_C	Carburized and/or Quenched and Tempered	4000 to 6000	75 to 200	Rough: .0005 Finish: .0002 max.	1/3 1/6	A60KV
			20 to 30	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A60KV

Maximum hole length is 2.5 times hole diameter.
Maximum wheel width is 1.5 times wheel diameter.
See section 16 for Cutting Fluid Recommendations
*Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter holes. For LARGER holes—use the same or softer grade wheel. For SMALLER holes—use a harder grade wheel. Also see section 20.2, Grinding Guidelines.

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
6. HIGH STRENGTH STEELS, WROUGHT 300M 4330V 4340 4340Si 98BV40 D6ac H11 H13 HP 9-4-20 HP 9-4-25 HP 9-4-30 HP 9-4-45	50 R_C max	Annealed, Normalized or Quenched and Tempered	4000 to 6000	75 to 200	Rough: .0005 Finish: .0002 max.	1/3 1/6	A60KV
			20 to 30	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A60KV
	Over 50 R_C	Quenched and Tempered	4000 to 5500	75 to 200	Rough: .0005 Finish: .0002 max.	1/3 1/6	A80IV
			20 to 28	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A80IV
7. MARAGING STEELS, WROUGHT ASTM A538 Grades A, B, C 120 Grade 180 Grade 200 Grade 250 Grade 300 Grade 350 Grade HY230	50 R_C max	Annealed or Maraged	5000 to 6500	75 to 200	Rough: .0005 Finish: .0002 max.	1/3 1/6	A60KV
			25 to 33	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A60KV
	Over 50 R_C	Maraged	4000 to 5500	75 to 200	Rough: .0005 Finish: .0002 max.	1/3 1/6	A80IV
			20 to 28	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A80IV
8. TOOL STEELS, WROUGHT **Group I** A2 H13 L6 P20 A3 H14 L7 P21 A4 H19 O1 S1 A6 H21 O2 S2 A8 H22 O6 S5 A9 H23 O7 S6 A10 H24 P2 S7 H10 H25 P4 W1 H11 H26 P5 W2 H12 L2 P6 W5 SAE J438b Types W108, W109, W110, W112, W209, W210, W310	50 R_C max	Annealed or Quenched and Tempered	5000 to 6500	75 to 200	Rough: .0005 Finish: .0002 max.	1/3 1/6	A60MV
			25 to 33	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A60MV
	Over 50 R_C	Quenched and Tempered	4000 to 6000	75 to 200	Rough: .0005 Finish: .0002 max.	1/3 1/6	A60KV
			20 to 30	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A60KV

Maximum hole length is 2.5 times hole diameter
Maximum wheel width is 1.5 times wheel diameter
See section 16 for Cutting Fluid Recommendations
*Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter holes. For LARGER holes—use the same or softer grade wheel. For SMALLER holes—use a harder grade wheel. Also see section 20.2, Grinding Guidelines

8.8 Internal Grinding

MATERIAL	HARDNESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFICATION* ANSI ISC
8. TOOL STEELS, WROUGHT (cont.) **Group II** D2 H42 M42 D3 M1 T1 D4 M2 T2 D5 M3-1 T4 F1 M10 T8 F2 M30	50 R_C max	Annealed or Quenched and Tempered	5000 to 6500	75 to 200	Rough .0005 Finish .0002 max.	1/3 1/6	A60LV
			25 to 33	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A60LV
	50 R_C to 58 R_C	Quenched and Tempered	4000 to 6000	75 to 200	Rough: .0005 Finish: .0002 max.	1/3 1/6	A50KV
			20 to 30	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A60KV
	Over 58 R_C	Quenched and Tempered	4000 to 5500	75 to 200	Rough: .0005 Finish: .0002 max.	1/3 1/6	A60JV
			20 to 26	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A60JV
Group III A7 M41 D7 M43 M3-2 M44 M6 M46 M7 M47 M33 T5 M34 T6 M36	50 R_C max	Annealed or Quenched and Tempered	4000 to 6000	75 to 200	Rough: .0005 Finish: .0002 max.	1/3 1/6	A60KV
			20 to 30	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A60KV
	50 R_C to 58 R_C	Quenched and Tempered	4000 to 6000	75 to 200	Rough: .0005 Finish: .0002 max.	1/3 1/6	A70KV
			20 to 30	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A70KV
	Over 58 R_C	Quenched and Tempered	4000 to 5500	75 to 200	Rough: .0005 Finish: .0002 max.	1/3 1/6	A60JV
			20 to 26	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A60JV

Maximum hole length is 2.5 times hole diameter
Maximum wheel width is 1.5 times wheel diameter.
See section 16 for Cutting Fluid Recommendations
*Wheel recommendations are for wet grinding 0.8- to 2-inch (20 to 50 mm) diameter holes. For LARGER holes—use the same or softer grade wheel. For SMALLER holes—use a harder grade wheel. Also see section 20.2, Grinding Guidelines.

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
Group IV M4 T15	50 R_C max.	Annealed or Quenched and Tempered	4000 to 6000	75 to 200	Rough: .0005 Finish: .0002 max.	1/3 1/6	A60JV
			20 to 30	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A60JV
	50 R_C to 58 R_C	Quenched and Tempered	4000 to 5500	75 to 200	Rough: .0005 Finish: .0002 max.	1/3 1/6	A80JV
			20 to 28	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A80JV
	Over 58 R_C	Quenched and Tempered	4000 to 5500	75 to 200	Rough: .0005 Finish: .0002 max.	1/3 1/6	A80IV
			20 to 28	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A80IV
9. NITRIDING STEELS, WROUGHT Nitralloy 125 Nitralloy 135 Nitralloy 135 Mod Nitralloy 225 Nitralloy 230 Nitralloy EZ Nitralloy N Nitrex 1	200 to 350	Annealed, Normalized or Quenched and Tempered	5000 to 6500	75 to 200	Rough: .0005 Finish. 0002 max.	1/3 1/6	A60KV
			25 to 35	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A60KV
	60 R_C to 65 R_C	Nitrided	4000 to 5500	75 to 200	Rough: .0005 Finish: 0002 max.	1/3 1/6	A80IV
			25 to 35	23 to 70	Rough: .013 Finish: .005 max.	1/3 1/6	A80IV
10. ARMOR PLATE, SHIP PLATE, AIRCRAFT PLATE, WROUGHT HY80 MIL-S-12560 HY100 MIL-S-16216 HY180	45 R_C max.	Annealed or Quenched and Tempered	5000 to 6500	75 to 200	Rough: 0005 Finish. .0002 max.	1/3 1/6	A60JV
			25 to 35	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A60JV

Maximum hole length is 2.5 times hole diameter
Maximum wheel width is 1 5 times wheel diameter.
See section 16 for Cutting Fluid Recommendations
*Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter holes. For LARGER holes—use the same or softer grade wheel. For SMALLER holes—use a harder grade wheel Also see section 20.2, Grinding Guidelines.

8.8 Internal Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm / m/s	WORK SPEED fpm / m/min	INFEED on dia. in/pass / mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI / ISO
12. FREE MACHINING STAINLESS STEELS, WROUGHT **Ferritic** 430F, 430F Se	135 to 185	Annealed	5000 to 6500	75 to 200	Rough .0005 / Finish, .0002 max.	1/3 / 1/6	A60KV
			25 to 33	23 to 60	Rough .013 / Finish .005 max.	1/3 / 1/6	A60KV
Austenitic 203EZ, 303, 303MA, 303Pb, 303 Plus X, 303Se	135 to 275	Annealed or Cold Drawn	5000 to 6500	75 to 200	Rough .0005 / Finish .0002 max.	1/3 / 1/6	C60KV
			25 to 33	23 to 60	Rough .013 / Finish .005 max.	1/3 / 1/6	C60KV
Martensitic 416, 416 Plus X, 416Se, 420F, 420F Se, 440F, 440F Se	135 to 240	Annealed or Cold Drawn	5000 to 6500	75 to 200	Rough: .0005 / Finish: .0002 max.	1/3 / 1/6	A60KV
			25 to 33	23 to 60	Rough: .013 / Finish: .005 max.	1/3 / 1/6	A60KV
	Over 275	Quenched and Tempered	5000 to 6500	50 to 150	Rough: .0005 / Finish. .0002 max	1/3 / 1/6	A60JV
			25 to 33	15 to 46	Rough .013 / Finish .005 max.	1/3 / 1/6	A60JV
13. STAINLESS STEELS, WROUGHT **Ferritic** 405, 409, 429, 430, 434, 436, 442, 446	135 to 185	Annealed	5000 to 6500	75 to 200	Rough: .0005 / Finish: .0002 max.	1/3 / 1/6	A60KV
			25 to 33	23 to 60	Rough .013 / Finish .005 max.	1/3 / 1/6	A60KV
Austenitic 201, 202, 301, 302, 302B, 304, 304L, 305, 308, 309, 309S, 310, 310S, 314, 316, 316L, 317, 321, 330, 347, 348, 384, 385	135 to 275	Annealed or Cold Drawn	5000 to 6500	75 to 200	Rough: .0005 / Finish: .0002 max.	1/3 / 1/6	C60KV
			25 to 33	23 to 60	Rough .013 / Finish .005 max.	1/3 / 1/6	C60KV

Maximum hole length is 2.5 times hole diameter.
Maximum wheel width is 1.5 times wheel diameter.
See section 16 for Cutting Fluid Recommendations.
*Wheel recommendations are for wet grinding 0.8- to 2-inch (20 to 50 mm) diameter holes. For LARGER holes—use the same or softer grade wheel. For SMALLER holes—use a harder grade wheel. Also see section 20.2, Grinding Guidelines

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm / m/s	WORK SPEED fpm / m/min	INFEED on dia. in/pass / mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI / ISO
Austenitic Nitronic 32 Nitronic 33 Nitronic 40 Nitronic 50 Nitronic 60	210 to 250	Annealed	5000 to 6500	75 to 200	Rough: .0005 Finish: .0002 max.	1/3 1/6	C60KV
			25 to 33	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	C60KV
	325 to 375	Cold Drawn	5000 to 6500	50 to 150	Rough: .0005 Finish: .0002 max	1/3 1/6	C60JV
			25 to 33	15 to 46	Rough: .013 Finish: .005 max.	1/3 1/6	C60JV
Martensitic 403 440A 410 440B 414 440C 420 501 422 502 431 Greek Ascoloy	135 to 275	Annealed	5000 to 6500	75 to 200	Rough: .0005 Finish: .0002 max	1/3 1/6	A60KV
			25 to 33	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A60KV
	Over 275	Quenched and Tempered	5000 to 6500	50 to 150	Rough: .0005 Finish: 0002 max	1/3 1/6	A60JV
			25 to 33	15 to 46	Rough: .013 Finish: .005 max.	1/3 1/6	A60JV
14. PRECIPITATION HARDENING STAINLESS STEELS, WROUGHT 15-5 PH AM-355 16-6 PH AM-363 17-4 PH Custom 450 17-7 PH Custom 455 17-14 Cu Mo HNM AF-71 PH 13-8 Mo AFC-77 PH 14-8 Mo Almar 362 (AM-352) PH 15-7 Mo AM-350 Stainless W	150 to 200	Solution Treated	5000 to 6500	75 to 200	Rough: .0005 Finish: .0002 max.	1/3 1/6	A60KV
			25 to 33	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A60KV
	275 to 440	Solution Treated or Hardened	5000 to 6500	50 to 150	Rough: .0005 Finish .0002 max	1/3 1/6	A60JV
			25 to 33	15 to 46	Rough: .013 Finish: .005 max.	1/3 1/6	A60JV

Maximum hole length is 2 5 times hole diameter.
Maximum wheel width is 1 5 times wheel diameter.
See section 16 for Cutting Fluid Recommendations.
*Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter holes. For LARGER holes—use the same or softer grade wheel. For SMALLER holes—use a harder grade wheel. Also see section 20.2, Grinding Guidelines.

8.8 Internal Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm / m/s	WORK SPEED fpm / m/min	INFEED on dia. in/pass / mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI / ISO
15. CARBON STEELS, CAST **Low Carbon** ASTM A426 Grade CP1 1010 1020 **Medium Carbon** ASTM A352 Grades LCA, LCB, LCC ASTM A356 Grade 1 1030 1040 1050	100 to 300	Annealed, Normalized, Normalized and Tempered, or Quenched and Tempered	5000 to 6500	75 to 200	Rough 0005 Finish 0002 max	1/3 1/6	A54MV
			25 to 33	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A54MV
	Over 50 R_C	Carburized and/or Quenched and Tempered	5000 to 6500	75 to 200	Rough 0005 Finish 0002 max	1/3 1/6	A60KV
			25 to 33	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A60KV
16. ALLOY STEELS, CAST **Low Carbon** ASTM A217 Grade WC9 ASTM A352 Grades LC3, LC4 ASTM A426 Grades CP2, CP5, CP5b, CP11, CP12, CP15, CP21, CP22 1320 4110 8020 2315 4120 8620 2320 4320 **Medium Carbon** ASTM A27. Grades N1, N2, U-60-30, 60-30, 65-35, 70-36, 70-40 ASTM A148 Grades 80-40, 80-50, 90-60, 105-85, 120-95, 150-125, 175-145 ASTM A216 Grades WCA, WCB, WCC ASTM A217 Grades WC1, WC4, WC5, WC6 ASTM A352 Grades LC1, LC2, LC2-1 ASTM A356 Grades 2, 5, 6, 8, 9, 10 ASTM A389 Grades C23, C24 ASTM A486. Classes 70, 90, 120 ASTM A487. Classes 1N, 2N, 4N, 6N, 8N, 9N, 10N, 5N, 1Q, 2Q, 4Q, 4QA, 6Q, 7Q, 8Q, 9Q, 10Q 1330 4130 80B30 8640 1340 4140 8040 9525 2325 4330 8430 9530 2330 4340 8440 9535 4125 4730 8630	150 to 400	Annealed, Normalized, Normalized and Tempered, or Quenched and Tempered	5000 to 6500	75 to 200	Rough: 0005 Finish 0002 max	1/3 1/6	A60MV
			25 to 33	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A60MV
	Over 50 R_C	Carburized and/or Quenched and Tempered	4000 to 6000	75 to 200	Rough .0005 Finish 0002 max	1/3 1/6	A60KV
			20 to 30	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A60KV

Maximum hole length is 2 5 times hole diameter.
Maximum wheel width is 1 5 times wheel diameter.
See section 16 for Cutting Fluid Recommendations.
*Wheel recommendations are for wet grinding 0 8- to 2-inch (20 to 50 mm) diameter holes For LARGER holes—use the same or softer grade wheel For SMALLER holes—use a harder grade wheel. Also see section 20.2, Grinding Guidelines

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
17. TOOL STEELS, CAST **Group I** ASTM A597: Grades CA-2, CH-12, CH-13, CO-1, CS-5	50 R_C max	Annealed or Quenched and Tempered	5000 to 6500	75 to 200	Rough: .0005 Finish: .0002 max	1/3 1/6	A60MV
			25 to 33	23 to 60	Rough: .013 Finish: .005 max	1/3 1/6	A60MV
	50 R_C to 58 R_C	Quenched and Tempered	4000 to 6000	75 to 200	Rough .0005 Finish .0002 max.	1/3 1/6	A80KV
			20 to 30	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A80KV
	Over 58 R_C	Quenched and Tempered	4000 to 5500	75 to 200	Rough: .0005 Finish: .0002 max.	1/3 1/6	A80JV
			20 to 30	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A80JV
Group II ASTM A597: Grades CD-2, CD-5	200 to 250	Annealed	5000 to 6500	75 to 200	Rough: .0005 Finish: .0002 max.	1/3 1/6	A60MV
			25 to 33	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A60MV
	48 R_C to 56 R_C	Quenched and Tempered	4000 to 6000	75 to 200	Rough: .0005 Finish: .0002 max.	1/3 1/6	A80KV
			20 to 30	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A80KV
	Over 56 R_C	Quenched and Tempered	4000 to 5500	75 to 200	Rough: .0005 Finish: .0002 max.	1/3 1/6	A80JV
			20 to 30	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A80JV

Maximum hole length is 2.5 times hole diameter.
Maximum wheel width is 1.5 times wheel diameter.
See section 13 for Cutting Fluid Recommendations.
*Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter holes. For LARGER holes—use the same or softer grade wheel. For SMALLER holes—use a harder grade wheel. Also see section 20.2, Grinding Guidelines.

8.8 Internal Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
18. STAINLESS STEELS, CAST **Ferritic** ASTM A217: Grades C5, C12 ASTM A296 Grades CB-30, CC-50, CE-30, CA6N, CA-6NM, CD4MCu ASTM A297 Grade HC ASTM A487 Class CA6NM ASTM A608: Grade HC30	135 to 185	Annealed	5000 to 6500	75 to 200	Rough: .0005 Finish .0002 max.	1/3 1/6	A60KV
			25 to 33	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A60KV
Austenitic ASTM A296 Grades CF-3, CF-3M, CF-8, CF-8C, CF-8M, CF-16F, CF-20, CG-8M, CG-12, CH-20, CK-20, CN-7M, CN-7MS ASTM A297: Grades HD, HE, HF, HH, HI, HK, HL HN, HP, HT, HU ASTM A351: Grades CF-3, CF-3A, CF-3M, CF-3MA, CF-8, CF-8A, CF-8C, CF-8M, CF-10MC, CH-8, CH-10, CH-20, CK-20, CN-7M, HK-30, HK-40, HT-30 ASTM A451, Grades CPF8A, CPF3, CPF3A, CPF3M, CPF8, CPF8C, CPF8C (Ta Max), CPF8M, CPF10MC, CPH8, CPH10, CPH20, CPK20 ASTM A452 Grades TP 304H, TP 316H, TP 347H ASTM A608: Grades HD50, HE35, HF30, HH30, HH33, HI35, HK30, HK40, HL30, HL40, HN40, HT50, HU50	135 to 210	Annealed, Normalized or As Cast	5000 to 6500	75 to 200	Rough: .0005 Finish .0002 max.	1/3 1/6	C60KV
			25 to 33	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	C60KV
Martensitic ASTM A217: Grade CA-15 ASTM A296: Grades CA-15, CA-15M, CA-40 ASTM A426 Grades CP7, CP9, CPCA15 ASTM A487: Classes CA15a, CA-15M	135 to 225	Annealed, Normalized or Normalized and Tempered	5000 to 6500	75 to 200	Rough: .0005 Finish .0002 max	1/3 1/6	A60KV
			25 to 33	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A60KV
	Over 275	Quenched and Tempered	5000 to 6500	50 to 150	Rough: .0005 Finish. .0002 max.	1/3 1/6	A60JV
			25 to 33	15 to 46	Rough: .013 Finish: .005 max.	1/3 1/6	A60JV

Maximum hole length is 2 5 times hole diameter
Maximum wheel width is 1 5 times wheel diameter.
See section 16 for Cutting Fluid Recommendations
*Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter holes. For LARGER holes—use the same or softer grade wheel For SMALLER holes—use a harder grade wheel Also see section 20 2, Grinding Guidelines

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
19. PRECIPITATION HARDENING STAINLESS STEELS, CAST ASTM A351 Grade CD-4MCu ACI Grade CB-7Cu ACI Grade CD-4MCu 17-4 PH AM-355	325 to 450	Solution Treated or Solution Treated and Aged	5000 to 6500	50 to 150	Rough: .0005 Finish: .0002 max	1/3 1/6	A60JV
			25 to 33	15 to 46	Rough: .013 Finish: .005 max.	1/3 1/6	A60JV
20. AUSTENITIC MANGANESE STEELS, CAST ASTM A128: Grades A, B-1, B-2, B-3, B-4, C, D, E-1, E-2, F	150 to 220	Annealed	5000 to 6500	75 to 200	Rough: .0005 Finish: .0002 max.	1/3 1/6	A46JV
			25 to 33	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A46JV
21. GRAY CAST IRONS **Ferritic** ASTM A48 Class 20 SAE J431c. Grade G1800 **Pearlitic- Ferritic** ASTM A48 Class 25 SAE J431c. Grade G2500 **Pearlitic** ASTM A48 Classes 30, 35, 40 SAE J431c Grade G3000 **Pearlitic + Free Carbides** ASTM A48. Classes 45, 50 SAE J431c. Grades G3500, G4000 **Pearlitic or Acicular + Free Carbides** ASTM A48. Classes 55, 60	45 R_C max.	As Cast, Annealed or Quenched and Tempered	5000 to 6500	75 to 200	Rough: .002 Finish: .0002 max.	1/3 1/6	C46JV or A46KV
			25 to 33	23 to 60	Rough: .050 Finish: .005 max.	1/3 1/6	C46JV or A46KV
	45 R_C to 52 R_C	As Cast, Annealed or Quenched and Tempered	5000 to 6500	75 to 200	Rough: .002 Finish: 0002 max.	1/3 1/6	C54JV or A60JV
			25 to 33	23 to 60	Rough: .050 Finish: .005 max.	1/3 1/6	C54JV or A60JV
	48 R_C to 60 R_C	Flame or Induction Hardened	5000 to 6500	75 to 200	Rough: .001 Finish: .0002 max.	1/3 1/6	C60IV or A60IV
			25 to 33	23 to 60	Rough: .025 Finish: .005 max.	1/3 1/6	C60IV or A60IV
Austenitic (NI-RESIST) ASTM A436: Types 1, 1b, 2, 2b, 3, 4, 5, 6	100 to 250	As Cast	5000 to 6500	75 to 200	Rough: .0006 Finish: .0003 max.	1/3 1/6	Rough: A36HV Finish: A60HV
			25 to 33	23 to 60	Rough: .015 Finish: .008 max.	1/3 1/6	Rough: A36HV Finish: A60HV

Maximum hole length is 2.5 times hole diameter
Maximum wheel width is 1.5 times wheel diameter.
See section 16 for Cutting Fluid Recommendations.
*Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter holes. For LARGER holes—use the same or softer grade wheel. For SMALLER holes—use a harder grade wheel. Also see section 20.2, Grinding Guidelines.

8.8 Internal Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
22. COMPACTED GRAPHITE CAST IRONS	185 to 225	As Cast	5000 to 6500	75 to 200	Rough: 002 Finish: 0002 max.	1/3 1/6	C46JV or A46KV
			25 to 33	23 to 60	Rough: .050 Finish: .005 max.	1/3 1/6	C46JV or A46KV
23. DUCTILE CAST IRONS **Ferritic** ASTM A536, Grades 60-40-18, 65-45-12 SAE J434c: Grades D4018, D4512 **Ferritic- Pearlitic** ASTM A536: Grade 80-55-06 SAE J434c: Grade D5506 **Pearlitic- Martensitic** ASTM A536: Grade 100-70-03 SAE J434c: Grade D7003 **Martensitic** ASTM A536: Grade 120-90-02 SAE J434c: Grade DQ&T	52 R_C max.	Annealed, As Cast, Normalized and Tempered or Quenched and Tempered	5000 to 6500	75 to 200	Rough: .002 Finish: .0002 max.	1/3 1/6	C54JV or A60JV
			25 to 33	23 to 60	Rough: .050 Finish: .005 max.	1/3 1/6	C54JV or A60JV
	53 R_C to 60 R_C	Flame or Induction Hardened	5000 to 6500	75 to 200	Rough: .001 Finish: .0002 max.	1/3 1/6	C60IV or A60IV
			25 to 33	23 to 60	Rough: .025 Finish: .005 max.	1/3 1/6	C60IV or A60IV
Austenitic (NI-RESIST Ductile) ASTM A439: Types D-2, D-2B, D-2C, D-3, D-3A, D-4, D-5, D-5B ASTM A571: Type D-2M	120 to 275	Annealed	5000 to 6500	75 to 200	Rough: .0006 Finish: .0003 max.	1/3 1/6	Rough: A36HV Finish: A60HV
			25 to 33	23 to 60	Rough: .015 Finish: .005 max.	1/3 1/6	Rough: A36HV Finish: A60HV
24. MALLEABLE CAST IRONS **Ferritic** ASTM A47: Grades 32510, 35018 ASTM A602: Grade M3210 SAE J158: Grade M3210 **Pearlitic** ASTM A220: Grades 40010, 45006, 45008, 50005 ASTM A602: Grade M4504, M5003 SAE J158, Grades M4504, M5003 **Tempered Martensite** ASTM A220: Grades 60004, 70003, 80002, 90001 ASTM A602: Grades M5503, M7002, M8501 SAE J158 Grades M5503, M7002, M8501	52 R_C max.	Malleablized or Malleablized and Heat Treated	5000 to 6500	75 to 200	Rough: .002 Finish: .0002 max.	1/3 1/6	C54JV or A60JV
			25 to 33	23 to 60	Rough: .050 Finish: .005 max.	1/3 1/6	C54JV or A60JV
	Over 52 R_C	Flame or Induction Hardened	5000 to 6500	75 to 200	Rough: .001 Finish: .0002 max.	1/3 1/6	C60IV or A60IV
			25 to 33	23 to 60	Rough: .025 Finish: .005 max.	1/3 1/6	C60IV or A60IV

Maximum hole length is 2.5 times hole diameter
Maximum wheel width is 1.5 times wheel diameter
See section 16 for Cutting Fluid Recommendations
*Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter holes. For LARGER holes—use the same or softer grade wheel. For SMALLER holes—use a harder grade wheel. Also see section 20.2, Grinding Guidelines.

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
25. WHITE CAST IRONS (ABRASION RESISTANT) ASTM A532 Class I, Types A, B, C, D Class II, Types A, B, C, D, E Class III, Type A	60 R_C max	As Cast, Annealed or Hardened	5000 to 6500	75 to 200	Rough .001 Finish .0002 max	1/3 1/6	C60IV
			25 to 33	23 to 60	Rough .025 Finish .005 max	1/3 1/6	C60IV
26. HIGH SILICON CAST IRONS Durlron Duriclor ASTM A518	52 R_C	As Cast	5000 to 6500	75 to 200	Rough .001 Finish: 0002 max.	1/3 1/6	A46LV
			25 to 33	23 to 60	Rough .025 Finish	1/3 1/6	A46LV
27. CHROMIUM-NICKEL ALLOY CASTINGS ASTM A560: Grades 50Cr-50Ni, 60Cr-40Ni	275 to 375	As Cast	5000 to 6500	50 to 150	Rough: .0005 Finish: .0002 max.	1/3 1/6	C60JV
			25 to 33	15 to 46	Rough .013 Finish .005 max.	1/3 1/6	C60JV
28. ALUMINUM ALLOYS, WROUGHT EC, 1060, 1100, 1145, 1175, 1235, 2011, 2014, 2017, 2018, 2021, 2024, 2025, 2117 2218, 2219, 2618, 3003, 3004, 3005, 4032, 5005, 5050, 5052, 5056, 5083, 5086, 5154 5252, 5254, 5454, 5456, 5457, 5652, 5657, 5053, 6061, 6063, 6066, 6070, 6101, 6151 6253, 6262, 6463, 6951, 7001, 7004, 7005, 7039, 7049, 7050, 7075, 7079, 7175, 7178	30 to 150 500kg	Cold Drawn or Solution Treated and Aged	5000 to 6500	75 to 200	Rough: .003 Finish: 0002 max.	1/3 1/6	C46JV
			25 to 33	23 to 60	Rough: .075 Finish .005 max.	1/3 1/6	C46JV

Maximum hole length is 2.5 times hole diameter.
Maximum wheel width is 1.5 times wheel diameter.
See section 16 for Cutting Fluid Recommendations.
*Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter holes. For LARGER holes—use the same or softer grade wheel. For SMALLER holes—use a harder grade wheel. Also see section 20.2, Grinding Guidelines

8.8 Internal Grinding

MATERIAL	HARD-NESS	CONDITION	WHEEL SPEED	WORK SPEED	INFEED on dia.	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION*
	Bhn		fpm m/s	fpm m/min	in/pass mm/pass		ANSI ISO
29. ALUMINUM ALLOYS, CAST **Sand and Permanent Mold** A140 295.0 514.0 A712.0 201.0 B295.0 A514.0 D712.0 208.0 308.0 B514.0 713.0 213.0 319.0 520.0 771.0 222.0 355.0 535.0 850.0 224.0 C355.0 705.0 A850.0 242.0 B443.0 707.0 B850.0 Hiduminium RR-350 **Die Castings** C443.0 518.0	40 to 125 500kg	As Cast or Solution Treated and Aged	5000 to 6500	75 to 200	Rough: .003 Finish: .0002 max.	1/3 1/6	C46JV
			25 to 33	23 to 60	Rough: .075 Finish: .005 max.	1/3 1/6	C46JV
Sand and Permanent Mold 328.0 356.0 A332.0 A356.0 F332.0 357.0 333.0 359.0 354.0 **Die Castings** 360.0 A380.0 390.0 A413.0 A360.0 383.0 392.0 380.0 A384.0 413.0	40 to 125 500kg	As Cast or Solution Treated and Aged	5000 to 6500	75 to 200	Rough: .003 Finish: .0002 max.	1/3 1/6	A60HV
			25 to 33	23 to 60	Rough: .075 Finish: .005 max.	1/3 1/6	A60HV
30. MAGNESIUM ALLOYS, WROUGHT‡‡ AZ21A HK31A AZ31B HM21A AZ31C HM31A AZ61A ZK40A AZ80A ZK60A	50 to 90 500kg	Annealed, Cold Drawn or Solution Treated and Aged	5000 to 6500	75 to 200	Rough: .003 Finish: .0002 max.	1/3 1/6	C46JV
			25 to 33	23 to 60	Rough: .075 Finish: .005 max.	1/3 1/6	C46JV
31. MAGNESIUM ALLOYS, CAST‡‡ AM60A AZ91C ZE41A AM100A AZ92A ZE63A AS41A EZ33A ZH62A AZ63A HK31A ZK51A AZ81A HZ32A ZK61A AZ91A K1A AZ91B QE22A	50 to 90 500kg	As Cast, Annealed or Solution Treated and Aged	5000 to 6500	75 to 200	Rough: .003 Finish: .0002 max.	1/3 1/6	C46JV
			25 to 33	23 to 60	Rough: .075 Finish: .005 max.	1/3 1/6	C46JV

Maximum hole length is 2.5 times hole diameter.
Maximum wheel width is 1.5 times wheel diameter
See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter holes. For LARGER holes—use the same or softer grade wheel. For SMALLER holes—use a harder grade wheel. Also see section 20.2, Grinding Guidelines

‡‡CAUTION Potential Fire Hazard. Exercise caution in grinding and disposing of swarf. Do NOT use water or water-miscible cutting fluids for magnesium alloys

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
32. TITANIUM ALLOYS, WROUGHT‡‡							
Commercially Pure							
99.5	110 to 275	Annealed	4000 to 5000	50 to 150	Rough: .0005	1/3	C60JV‡
99.2					Finish: .0002 max	1/6	
99.0			20 to 25	15 to 46	Rough: .013	1/3	C60JV‡
98.9					Finish: .005 max.	1/6	
Ti-0.2Pd							
TiCODE-12							
Alpha and Alpha-Beta Alloys							
Ti-8Mn	300 to 380	Annealed	4000 to 5000	50 to 150	Rough: .0005	1/3	C60JV‡
Ti-1Al-8V-5Fe					Finish: .0002 max.	1/6	
Ti-2Al-11Sn-5Zr-1Mo			20 to 25	15 to 46	Rough: .013	1/3	C60JV‡
Ti-3Al-2.5V					Finish: .005 max.	1/6	
Ti-5Al-2Sn-2Zr-4Mo-4Cr (Ti-17)							
Ti-5Al-2.5Sn							
Ti-5Al-2.5Sn ELI							
Ti-5Al-6Sn-2Zr-1Mo							
Ti-6Al-2Cb-1Ta-0.8Mo							
Ti-6Al-4V	320 to 440	Solution Treated and Aged	4000 to 5000	50 to 150	Rough: .0005	1/3	C60JV‡
Ti-6Al-4V ELI					Finish: .0002 max.	1/6	
Ti-6Al-6V-2Sn			20 to 25	15 to 46	Rough: .013	1/3	C60JV‡
Ti-6Al-2Sn-4Zr-2Mo					Finish: .005 max.	1/6	
Ti-6Al-2Sn-4Zr-2Mo-.25Si							
Ti-6Al-2Sn-4Zr-6Mo							
Ti-7Al-4Mo							
Ti-8Al-1Mo-1V							
Beta Alloys							
Ti-3Al-8V-6Cr-4Mo-4Zr	275 to 350	Annealed or Solution Treated	4000 to 5000	50 to 150	Rough: .0005	1/3	C60JV‡
Ti-8Mo-8V-2Fe-3Al					Finish: .0002 max	1/6	
Ti-11.5Mo-6Zr-4.5Sn			20 to 25	15 to 46	Rough: .013	1/3	C60JV‡
Ti-10V-2Fe-3Al					Finish: .005 max.	1/6	
Ti-13V-11Cr-3Al							
	350 to 440	Solution Treated and Aged	4000 to 5000	50 to 150	Rough: .0005	1/3	C60JV‡
					Finish: 0002 max.	1/6	
			20 to 25	15 to 46	Rough: .013	1/3	C60JV‡
					Finish: .005 max.	1/6	
33. TITANIUM ALLOYS, CAST‡‡							
Commercially Pure							
99.0	150 to 250	As Cast or As Cast and Annealed	4000 to 5000	50 to 150	Rough: 0005	1/3	C60JV‡
Ti-0.2Pd					Finish: 0002 max.	1/6	
ASTM B367 Grades C-1, C-2, C-3, C-4, C-7A, C-7B, C-8A, C-8B			20 to 25	15 to 46	Rough: .013	1/3	C60JV‡
					Finish: .005 max.	1/6	

Maximum hole length is 2.5 times hole diameter.
Maximum wheel width is 1.5 times wheel diameter.
See section 16 for Cutting Fluid Recommendations
*Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter holes. For LARGER holes—use the same or softer grade wheel. For SMALLER holes—use a harder grade wheel. Also see section 20.2, Grinding Guidelines

‡Use friable (green grit) silicon carbide
‡‡CAUTION: Potential Fire Hazard. Exercise caution in grinding and disposing of swarf

8.8 Internal Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm / m/s	WORK SPEED fpm / m/min	INFEED on dia. in/pass / mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI / ISO
33. TITANIUM ALLOYS, CAST‡‡ (cont.) **Alpha and Alpha-Beta Alloys** Ti-5Al-2.5Sn Ti-6Al-4V Ti-6Al-2Sn-4Zr-2Mo Ti-8Al-1Mo-1V ASTM B367 Grades C-5, C-6	300 to 350	As Cast or As Cast and Annealed	4000 to 5000	50 to 150	Rough: 0005 Finish: 0002 max	1/3 1/6	C60JV‡
			20 to 25	15 to 45	Rough: .013 Finish: .005 max.	1/3 1/6	C60JV‡
34. COPPER ALLOYS, WROUGHT 101 116 143 182 102 119 145 184 104 120 147 185 105 121 150 187 107 122 155 189 109 125 162 190 110 127 165 191 111 128 170†† 192 113 129 172†† 194 114 130 173†† 195 115 142 175††	10 R_B to 70 R_B	Annealed	5000 to 6500	75 to 200	Rough: .002 Finish: .0002 max	1/3 1/6	C46JV
			25 to 33	23 to 60	Rough: .050 Finish: .005 max.	1/3 1/6	C46JV
	60 R_B to 100 R_B	Cold Drawn	5000 to 6500	75 to 200	Rough: .002 Finish: .0002 max.	1/3 1/6	C46JV
			25 to 33	23 to 60	Rough: .050 Finish: .005 max.	1/3 1/6	C46JV
210 332 368 464 220 335 370 465 226 340 377 466 230 342 385 467 240 345 411 482 260 350 413 485 268 353 425 667 270 356 435 687 280 360 442 688 314 365 443 694 316 366 444 330 367 445	10 R_B to 70 R_B	Annealed	5000 to 6500	75 to 200	Rough: .002 Finish: .0002 max.	1/3 1/6	C46JV
			25 to 33	23 to 60	Rough: .050 Finish: .005 max.	1/3 1/6	C46JV
	60 R_B to 100 R_B	Cold Drawn	5000 to 6500	75 to 200	Rough: .002 Finish .0002 max.	1/3 1/6	C46JV
			25 to 33	23 to 60	Rough: .050 Finish: .005 max.	1/3 1/6	C46JV
505 613 632 510 614 638 511 618 642 521 619 651 524 623 655 544 624 674 608 625 675 610 630	10 R_B to 70 R_B	Annealed	5000 to 6500	75 to 200	Rough: .002 Finish: .0002 max.	1/3 1/6	C46JV
			25 to 33	23 to 60	Rough: .050 Finish: .005 max.	1/3 1/6	C46JV

Maximum hole length is 2.5 times hole diameter.
Maximum wheel width is 1.5 times wheel diameter.
See section 16 for Cutting Fluid Recommendations.
*Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter holes. For LARGER holes—use the same or softer grade wheel. For SMALLER holes—use a harder grade wheel. Also see section 20.2, Grinding Guidelines.

‡ Use friable (green grit) silicon carbide.
†† CAUTION: Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions.
‡‡ CAUTION: Potential Fire Hazard. Exercise caution in grinding and disposing of swarf.

MATERIAL			HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
34. COPPER ALLOYS, WROUGHT (cont.) (materials listed on preceding page)			60 R_B to 100 R_B	Cold Drawn	5000 to 6500	75 to 200	Rough: .002 Finish: .0002 max.	1/3 1/6	C46JV
					25 to 33	23 to 60	Rough: .050 Finish: .005 max.	1/3 1/6	C46JV
706	752		10 R_B to 70 R_B	Annealed	5000 to 6500	75 to 200	Rough: .002 Finish: .0002 max.	1/3 1/6	C46JV
710	754								
715	757								
725	770								
745	782				20 to 33	23 to 60	Rough: .050 Finish: .005 max.	1/3 1/6	C46JV
			60 R_B to 100 R_B	Cold Drawn	5000 to 6500	75 to 200	Rough: .002 Finish: .0002 max.	1/3 1/6	C46JV
					25 to 48	23 to 60	Rough: .050 Finish: .005 max.	1/3 1/6	C46JV
35. COPPER ALLOYS, CAST									
801	814	824††	40 to 200 500kg	As Cast or Heat Treated	5000 to 6500	75 to 200	Rough: .002 Finish: .0002 max.	1/3 1/6	C46JV
803	815	825††							
805	817††	826††							
807	818††	827††							
809	820††	828††							
811	821††								
813	822††				25 to 33	23 to 60	Rough: .050 Finish: .005 max.	1/3 1/6	C46JV
			34 R_C to 45 R_C	Heat Treated	5000 to 6500	75 to 200	Rough: .002 Finish: .0002 max.	1/3 1/6	A54KV
					35 to 45	23 to 60	Rough: .050 Finish: .005 max.	1/3 1/6	A54KV
833	854	867	35 to 200 500kg	As Cast	5000 to 6500	75 to 200	Rough: .002 Finish: .0002 max.	1/3 1/6	C46JV
834	855	868							
836	857	872							
838	858	874							
842	861	875							
844	862	876							
848	863	878							
852	864	879							
853	865				40 to 50	23 to 60	Rough: .050 Finish: .005 max.	1/3 1/6	C46JV

Maximum hole length is 2.5 times hole diameter.
Maximum wheel width is 1.5 times wheel diameter.
See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding 0.8- to 2-inch (20 to 50 mm) diameter holes. For LARGER holes—use the same or softer grade wheel. For SMALLER holes—use a harder grade wheel. Also see section 20.2 Grinding Guidelines.

††CAUTION. Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions

8.8 Internal Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in./pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
35. COPPER ALLOYS, CAST (cont.) 902 916 934 948 903 917 935 952 905 922 937 953 907 923 938 954 909 925 939 955 910 926 943 956 911 927 944 957 913 928 945 958 915 932 947	40 to 100 500kg	As Cast	5000 to 6500	75 to 200	Rough .002 Finish. .0002 max.	1/3 1/6	C46JV
			25 to 33	23 to 60	Rough: .050 Finish: .005 max.	1/3 1/6	C46JV
	Over 100 500kg	As Cast or Heat Treated	5000 to 6500	75 to 200	Rough .002 Finish. .0002 max.	1/3 1/6	A54KV
			25 to 33	20 to 60	Rough: .050 Finish: .005 max.	1/3 1/6	A54KV
962 963 964 966†† 973 974 976 978 993	50 to 100 500kg	As Cast	5000 to 6500	75 to 200	Rough: .002 Finish: .0002 max.	1/3 1/6	C46JV
			25 to 33	23 to 60	Rough: .050 Finish: .005 max.	1/3 1/6	C46JV
	Over 100 500kg	As Cast or Heat Treated	5000 to 6500	75 to 200	Rough: .002 Finish: .0002 max.	1/3 1/6	A54KV
			25 to 33	23 to 60	Rough: .050 Finish: .005 max.	1/3 1/6	A54KV
36. NICKEL ALLOYS, WROUGHT AND CAST Nickel 200 Nickel 201 Nickel 205 Nickel 211 Nickel 220 Nickel 230	80 to 170	Annealed or Cold Drawn	5000 to 6000	50 to 150	Rough: .0005 Finish: .0002 max.	1/3 1/6	C54JV
			25 to 30	15 to 46	Rough: .013 Finish: .005 max.	1/3 1/6	C54JV
MONEL Alloy 400 MONEL Alloy 401 MONEL Alloy 404 MONEL Alloy R405 ASTM A296. Grades CZ-100, M-35 ASTM A494: Grades CZ-100, M-35	115 to 240	Annealed, Cold Drawn or Cast	5000 to 6000	50 to 150	Rough: .0005 Finish: .0002 max.	1/3 1/6	C54JV
			25 to 30	15 to 46	Rough: .013 Finish: .005 max.	1/3 1/6	C54JV

Maximum hole length is 2.5 times hole diameter.
Maximum wheel width is 1.5 times wheel diameter.
See section 16 for Cutting Fluid Recommendations
*Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter holes. For LARGER holes—use the same or softer grade wheel. For SMALLER holes—use a harder grade wheel. Also see section 20.2, Grinding Guidelines

††CAUTION: Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
DURANICKEL Alloy 301 MONEL Alloy 502 MONEL Alloy K500 NI-SPAN-C Alloy 902 PERMANICKEL Alloy 300	150 to 320	Solution Treated	5000 to 6000	50 to 150	Rough: 0005 Finish: .0002 max.	1/3 1/6	C60JV
			25 to 30	15 to 46	Rough: .013 Finish: .005 max.	1/3 1/6	C60JV
	330 to 360	Aged	5000 to 6000	50 to 150	Rough: .0005 Finish .0002 max.	1/3 1/6	C60JV
			25 to 30	15 to 46	Rough: .013 Finish: .005 max.	1/3 1/6	C60JV
37. BERYLLIUM NICKEL ALLOYS, WROUGHT AND CAST†† Berylco 440 Berylco 41C Berylco 42C Berylco 43C Brush Alloy 200C Brush Alloy 220C Brush Alloy 260C	200 to 250	As Cast or Solution Treated	5000 to 6000	50 to 150	Rough: .0005 Finish. .0002 max	1/3 1/6	A46KV
			25 to 30	15 to 46	Rough: .013 Finish: .005 max.	1/3 1/6	A46KV
	283 to 425	Hardened or Aged	5000 to 6000	50 to 150	Rough: .0005 Finish: .0002 max.	1/3 1/6	A60JV
			25 to 30	15 to 46	Rough: .013 Finish: .005 max.	1/3 1/6	A60JV
	47 R_C to 52 R_C	Hardened or Aged	5000 to 5000	50 to 150	Rough. .0005 Finish .0002 max.	1/3 1/6	A60IV
			25 to 30	15 to 46	Rough: .013 Finish: .005 max.	1/3 1/6	A60IV
38. NITINOL ALLOYS, WROUGHT Nitinol 55Ni-45Ti Nitinol 56Ni-44Ti Nitinol 60Ni-40Ti	210 to 340	Wrought or Annealed	5000	50 to 150	Rough: .0005 Finish: .0002 max.	1/3 1/6	C60JV
			25	15 to 46	Rough: .013 Finish: .005 max.	1/3 1/6	C60JV

Maximum hole length is 2 5 times hole diameter.
Maximum wheel width is 1.5 times wheel diameter.
See section 16 for Cutting Fluid Recommendations.
*Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter holes. For LARGER holes—use the same or softer grade wheel For SMALLER holes—use a harder grade wheel. Also see section 20.2, Grinding Guidelines

††CA TION Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions.

8.8 Internal Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
38. NITINOL ALLOYS, WROUGHT (cont.) (materials listed on preceding page)	48 R_C to 52 R_C	Quenched	5000	50 to 150	Rough .0005 Finish .0002 max	1/3 1/6	C60JV
			25	15 to 45	Rough .013 Finish .005 max	1/3 1/6	C60JV
39. HIGH TEMPERATURE ALLOYS, WROUGHT AND CAST **Nickel Base, Wrought** AF2-1DA Astroloy Haynes Alloy 263 IN-102 Incoloy Alloy 901 Incoloy Alloy 903 Inconel Alloy 617 Inconel Alloy 625 Inconel Alloy 700 Inconel Alloy 702 Inconel Alloy 706 Inconel Alloy 718 Inconel Alloy 721 Inconel Alloy 722 Inconel Alloy X-750 Inconel Alloy 751 M252 Nimonic 75 Nimonic 80 Nimonic 90 Nimonic 95 Rene 41 Rene 63 Rene 77 Rene 95 Udimet 500 Udimet 700 Udimet 710 Unitemp 1753 Waspaloy	200 to 390	Annealed or Solution Treated	3000 to 4000	50 to 150	Rough. .0005 Finish .0002 max	1/3 1/6	A60JV
			15 to 20	15 to 45	Rough .013 Finish .005 max	1/3 1/6	A60JV
	300 to 475	Solution Treated and Aged	3000 to 4000	50 to 150	Rough .0005 Finish .0002 max	1/3 1/6	A60JV
			15 to 20	15 to 45	Rough .013 Finish .005 max	1/3 1/6	A60JV

Maximum hole length is 2.5 times hole diameter
Maximum wheel width is 1.5 times wheel diameter.
See section 16 for Cutting Fluid Recommendations.
*Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter holes. For LARGER holes—use the same or softer grade wheel. For SMALLER holes—use a harder grade wheel. Also see section 20.2, Grinding Guidelines

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev of work	WHEEL IDENTIFI-CATION* ANSI ISO
Nickel Base, Wrought Hastelloy Alloy B Hastelloy Alloy B-2 Hastelloy Alloy C Hastelloy Alloy C-276 Hastelloy Alloy G Hastelloy Alloy S Hastelloy Alloy X Incoloy Alloy 804 Incoloy Alloy 825 Inconel Alloy 600 Inconel Alloy 601 Refractaloy 26 Udimet 630	140 to 220	Annealed or Solution Treated	3000 to 4000	50 to 150	Rough: .0005 Finish: .0002 max.	1/3 1/6	A60JV
			15 to 20	15 to 46	Rough: .013 Finish: .005 max.	1/3 1/6	A60JV
	240 to 310	Cold Drawn or Aged	3000 to 4000	50 to 150	Rough: .0005 Finish: .0002 max.	1/3 1/6	A60JV
			15 to 20	15 to 46	Rough: .013 Finish: .005 max.	1/3 1/6	A60JV
Nickel Base, Wrought TD-Nickel†† TD-Ni-Cr††	180 to 200	As Rolled	5000	50 to 150	Rough: .0005 Finish: .0002 max	1/3 1/6	A60JV
			25 to 30	15 to 46	Rough: .013 Finish: .005 max.	1/3 1/6	A60JV
Nickel Base, Cast B-1900 GMR-235 GMR-235D Hastelloy Alloy B Hastelloy Alloy C Hastelloy Alloy D IN-100 (Rene 100) IN-738 IN-792 Inconel Alloy 713C Inconel Alloy 718 M252 MAR-M200 MAR-M246 MAR-M421 MAR-M432 Rene 80 Rene 125 SEL SEL 15 TRW VI A Udimet 500 Udimet 700 ASTM A296: Grades CW-12M, N-12M, CY-40 ASTM A297: Grades HW, HX ASTM A494: Grades N-12M-1, N-12M-2, CY-40, CW 12M-1, CW-12M-2 ASTM A608: Grades HW50, HX50	200 to 425	As Cast or Cast and Aged	3000 to 4000	50 to 150	Rough: .0005 Finish: .0002 max.	1/3 1/6	A60JV
			15 to 20	5 to 15	Rough: .013 Finish: .005 max.	1/3 1/6	A60JV

Maximum hole length is 2.5 times hole diameter.
Maximum wheel width is 1.5 times wheel diameter.
See section 16 for Cutting Fluid Recommendations
*Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter holes. For LARGER holes—use the same or softer grade wheel. For SMALLER holes—use a harder grade wheel. Also see section 20.2, Grinding Guidelines.

††CAUTION: Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions.

8.8 Internal Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
39. HIGH TEMPERATURE ALLOYS, WROUGHT AND CAST (cont.)							
Cobalt Base, Wrought							
AiResist 213	180 to 230	Solution Treated	3000 to 4000	50 to 150	Rough: .0005	1/3	A60JV
Haynes Alloy 25 (L605)					Finish: .0002 max.	1/6	
Haynes Alloy 188			15 to 20	15 to 46	Rough: .013	1/3	A60JV
J-1570					Finish: .005 max.	1/6	
MAR-M905							
MAR-M918							
S-816							
V-36	270 to 320	Solution Treated and Aged	3000 to 4000	50 to 150	Rough: .0005	1/3	A60JV
					Finish: .0002 max	1/6	
			15 to 20	15 to 46	Rough: .013	1/3	A60JV
					Finish: .005 max.	1/6	
Cobalt Base, Cast							
AiResist 13	220 to 290	As Cast or Cast and Aged	3000 to 4000	50 to 150	Rough: .0005	1/3	A60JV
AiResist 215					Finish: .0002 max.	1/6	
FSX-414			15 to 20	15 to 46	Rough: .013	1/3	A60JV
HS-6					Finish: .005 max.	1/6	
HS-21							
HS-31 (X-40)							
HOWMET #3							
MAR-M302							
MAR-M322							
MAR-M509							
NASA Co-W-Re	290 to 425	As Cast or Cast and Aged	3000 to 4000	50 to 150	Rough: .0005	1/3	A60JV
WI-52					Finish: .0002 max.	1/6	
X-45			15 to 20	15 to 46	Rough: .013	1/3	A60JV
					Finish: .005 max.	1/6	
Iron Base, Wrought							
A-286	180 to 230	Solution Treated	3000 to 4000	50 to 150	Rough: .0005	1/3	A60JV
Discaloy					Finish: .0002 max.	1/6	
Incoloy Alloy 800			15 to 20	15 to 46	Rough: .013	1/3	A60JV
Incoloy Alloy 800H					Finish: .005 max.	1/6	
Incoloy Alloy 801							
Incoloy Alloy 802							
N-155							
V-57							
W-545							
16-25-6							
19-9DL	250 to 320	Solution Treated and Aged	3000 to 4000	50 to 150	Rough: 0005	1/3	A60JV
					Finish: 0002 max.	1/6	
			15 to 20	15 to 46	Rough: .013	1/3	A60JV
					Finish: .005 max.	1/6	

Maximum hole length is 2.5 times hole diameter.
Maximum wheel width is 1.5 times wheel diameter.
See section 16 for Cutting Fluid Recommendations.
*Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter holes. For LARGER holes—use the same or softer grade wheel. For SMALLER holes—use a harder grade wheel. Also see section 20.2, Grinding Guidelines.

MATERIAL	HARDNESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFICATION* ANSI ISO
40. REFRACTORY ALLOYS, WROUGHT, CAST, P/M**							
Columbium †† ‡‡**							
C103 C129Y Cb-1Zr Cb-752 FS-85 FS-291 WC-3015	170 to 225	Stress Relieved	4000	50 to 150	Rough .001 Finish .0005 max	1/3 1/6	A60JV
			20	15 to 46	Rough: .025 Finish: .013 max.	1/3 1/6	A60JV
Molybdenum**							
Mo Mo-50Re TZC TZM	220 to 290	Stress Relieved	4000	50 to 150	Rough. .001 Finish .0005 max	1/3 1/6	A60JV
			20	15 to 46	Rough: .025 Finish: .013 max.	1/3 1/6	A60JV
Tantalum**							
ASTAR 811C T-111 T-222 Ta-10W Ta-Hf Ta63	200 to 250	Stress Relieved	4000	50 to 150	Rough .001 Finish .0005 max	1/3 1/6	A60JV
			20	15 to 46	Rough: .025 Finish: .013 max.	1/3 1/6	A60JV
Tungsten**							
85% density 93% density 96% density 100% density	180 to 320	Pressed and Sintered, Forged, or Arc Cast	2000	50 to 150	Rough .0005 Finish: .0002 max.	1/3 1/6	C60HV
			10	15 to 46	Rough: .013 Finish: .005 max.	1/3 1/6	C60HV
Tungsten - 2 Thoria ††**							
	260 to 320	Pressed and Sintered	2000	50 to 150	Rough .0005 Finish .0002 max.	1/3 1/6	C60HV
			10	15 to 46	Rough: .013 Finish: .005 max.	1/3 1/6	C60HV

Maximum hole length is 2 5 times hole diameter.
Maximum wheel width is 1 5 times wheel diameter
See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding 0 8- to 2-inch [20 to 50 mm] diameter holes For LARGER holes—use the same or softer grade wheel For SMALLER holes—use a harder grade wheel. Also see section 20 2, Grinding Guidelines

**Due to the brittleness of refractory alloys, cracking, chipping, flaking and breakout tend to occur, particularly on the edges of the machined surfaces

††CAUTION Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions

‡‡CAUTION: Potential Fire Hazard Exercise caution in grinding and disposing of swarf

8.8 Internal Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
40. REFRACTORY ALLOYS, WROUGHT, CAST, P/M (cont.)** **Tungsten Alloys**** GE-218 W-15Mo W-5Re W-25Re W-25Re-30Mo	260 to 320	As Cast	2000 10	50 to 150 15 to 46	Rough 0005 Finish 0002 max Rough .013 Finish .005 max.	1/3 1/6 1/3 1/6	C60HV C60HV
Tungsten Alloys** Gyromet Mallory 2000 W-10Ag W-7Ni-4Cu	290 to 320	Pressed and Sintered	2000 10	50 to 150 15 to 46	Rough 0005 Finish 0002 max. Rough .013 Finish .005 max.	1/3 1/6 1/3 1/6	C60HV C60HV
Tungsten Alloys** Anviloy 1100 Anvilloy 1150 Anvilloy 1200	290 to 320	Pressed and Sintered	3000 15	50 to 150 15 to 46	Rough .0005 Finish 0002 max. Rough .013 Finish .005 max.	1/3 1/6 1/3 1/6	C60HV C60HV
45. ZIRCONIUM ALLOYS, WROUGHT‡‡ Zr-2%Hf (Grade 11) Zr-0.001%Hf (Grade 21) Zircaloy 2 (Grade 32) Zircaloy 4 (Grade 34)	140 to 280	Rolled, Extruded or Forged	3000 15	50 to 150 15 to 46	Rough. .0005 Finish .0002 max. Rough .013 Finish .005 max.	1/3 1/6 1/3 1/6	C80KV C80KV
47. POWDER METAL ALLOYS§§ **Copper§§**	50 R_F to 70 R_F	As Sintered	5000 to 6500 30 to 35	75 to 200 23 to 61	Rough: .002 Finish. .0002 max Rough .050 Finish .005 max.	1/3 1/6 1/3 1/6	C46JV C46JV
Brasses§§ CZP-0218-T CZP-0218-U CZP-0218-W 90Cu-10Zn 90Cu-10Zn-0.5Pb 70Cu-30Zn 68.5Cu-30Zn-1.5Pb	35 R_H to 81 R_H	As Sintered	5000 to 6500 30 to 35	75 to 200 23 to 61	Rough: 002 Finish: .0002 max. Rough .050 Finish .005 max.	1/3 1/6 1/3 1/6	C46JV C46JV

Maximum hole length is 2.5 times hole diameter.
Maximum wheel width is 1.5 times wheel diameter.
See section 16 for Cutting Fluid Recommendations.

*Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter holes. For LARGER holes—use the same or softer grade wheel. For SMALLER holes—use a harder grade wheel. Also see section 20.2, Grinding Guidelines

**Due to the brittleness of refractory alloys, cracking, chipping, flaking and breakout tend to occur, particularly on the edges of the machined surfaces

‡‡CAUTION: Potential Fire Hazard. Exercise caution in grinding and disposing of swarf

§§Grinding of low density parts is not recommended because surface porosity will be reduced or lost.

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
Bronzes§§ CT-0010-N CT-0010-R CT-0010-S 95Cu-5Al 77Cu-15Pb-7Sn-1Fe-1C	30 R_F to 75 R_F	As Sintered	5000 to 6500	75 to 200	Rough .002 Finish .0002 max	1/3 1/6	C46JV
			25 to 33	23 to 60	Rough .050 Finish .005 max.	1/3 1/6	C46JV
Copper-Nickel Alloys§§ CZN-1818-T CZN-1818-U CZN-1818-W CZNP-1618-U CZNP-1618-W 90Cu-10Ni 62Cu-18Ni-18Zn-2Sn	22 R_H to 100 R_H	As Sintered	5000 to 6500	75 to 200	Rough .002 Finish .0002 max	1/3 1/6	C46JV
			25 to 33	25 to 60	Rough .050 Finish .005 max.	1/3 1/6	C46JV
Nickel§§	45 R_B	As Sintered	5000 to 6500	50 to 150	Rough .0005 Finish .0002 max	1/3 1/6	C60KV
			25 to 33	15 to 46	Rough .013 Finish .005 max.	1/3 1/6	C60KV
Nickel Alloys§§ 67Ni-30Cu-3Fe	34 R_B to 50 R_B	As Sintered	5000 to 6500	50 to 150	Rough .0005 Finish. .0002 max.	1/3 1/6	C60IV
			25 to 33	15 to 46	Rough .013 Finish .005 max.	1/3 1/6	C60IV
Refractory Metal Base§§ 87W-13Cu 85W-15Ag 74W-26Cu 72.5W-27.5Ag 65W-35Ag 56W + C-44Cu 55W-45Cu 51W-49Ag 50W + C-50Ag	101 to 260	As Sintered	2000	50 to 150	Rough .0005 Finish .0002 max	1/3 1/6	C60HV
			10	15 to 46	Rough .013 Finish .005 max.	1/3 1/6	C60HV

Maximum hole length is 2.5 times hole diameter.
Maximum wheel width is 1.5 times wheel diameter.
See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter holes. For LARGER holes—use the same or softer grade wheel. For SMALLER holes—use a harder grade wheel. Also see section 20.2, Grinding Guidelines

§§ Grinding of low-density parts is not recommended because surface porosity will be reduced or lost

8.8 Internal Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
47. POWDER METAL ALLOYS§§ (cont.) **Refractory Metal Base§§** 61Mo-39Ag 50Mo-50Ag	75 R_B to 82 R_B	As Sintered	4000	50 to 150	Rough .001 Finish .0005 max	1/3 1/6	A60JV
			20	15 to 46	Rough: .025 Finish: .013 max.	1/3 1/6	A60JV
Irons§§ F-0000-N F-0000-P F-0000-R F-0000-S F-0000-T	50 to 67 500kg	As Sintered	5000 to 6500	75 to 200	Rough: .002 Finish: .0002 max.	1/3 1/6	C46JV or A46KV
			25 to 33	23 to 60	Rough: .050 Finish: .005 max.	1/3 1/6	C46JV or A46KV
Steels§§ F-0008-P F-0008-S F-0005-S FC-0205-S FC-0208-P FC-0208-S FC-0508-P FC-1000-N FN-0205-S FN-0205-T FN-0405-R FN-0405-S FN-0405-T FX-1005-T FX-2008-T	101 to 426	As Sintered or Heat Treated	5000 to 6500	75 to 200	Rough. .0005 Finish· .0002 max.	1/3 1/6	A54MV
			25 to 33	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	A54MV
Stainless Steels§§ SS-303-R SS-304-R SS-316-R SS-410-R	107 to 285	As Sintered or Heat Treated	5000 to 6500	75 to 200	Rough: .0005 Finish: .0002 max.	1/3 1/6	C60KV
			25 to 33	23 to 60	Rough: .013 Finish: .005 max.	1/3 1/6	C60KV
Aluminum Alloys§§ 90 5Al-5Sn-4Cu 88 5Sn-4Pb-3Cu Al-1Mg-0 6Si-0.25Cu Al-0 6Mg-0.4Si Al-4 4Cu-0 8Si-0.4Mg	55 R_H to 98 R_H	Solution Treated and Aged	5000 to 6500	75 to 200	Rough: .003 Finish: .0002 max.	1/3 1/6	C46JV
			25 to 33	23 to 60	Rough: .075 Finish: .005 max.	1/3 1/6	C46JV

Maximum hole length is 2 5 times hole diameter.
Maximum wheel width is 1.5 times wheel diameter.
See section 16 for Cutting Fluid Recommendations

*Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter holes. For LARGER holes—use the same or softer grade wheel. For SMALLER holes—use a harder grade wheel. Also see section 20 2, Grinding Guidelines.

§§Grinding of low-density parts is not recommended because surface porosity will be reduced or lost

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
48. MACHINABLE CARBIDES Ferro-Tic	40 R_C to 51 R_C	Annealed	4000 to 6000	50 to 150	Rough 0005 Finish .0002 max.	1/3 1/6	A60JV
			20 to 30	15 to 46	Rough: .013 Finish: .005 max.	1/3 1/6	A60JV
	68 R_C to 70 R_C	Hardened and Tempered	—	—	—	—	†
			—	—	—	—	†
49. CARBIDES Titanium Carbide Tungsten Carbide	89 R_A to 94 R_A	—	5000 to 6000	50 to 100	Rough .0005 Finish: .0002 max	1/3 1/6	Rough: C60KV Finish: C120JV‡
			25 to 30	5 to 30	Rough: .013 Finish: .005 max.	1/3 1/6	Rough: C60KV Finish: C120JV‡
50. FREE MACHINING MAGNETIC ALLOYS Magnetic Core Iron-FM (up to 2.5% Si)	185 to 240	Wrought	5000 to 6500	75 to 200	Rough .001 Finish: .0002 max.	1/3 1/6	A60LV
			25 to 33	23 to 60	Rough: .025 Finish: .005 max.	1/3 1/6	A60LV
Hi Perm 49-FM	185 to 240	Wrought	5000 to 6000	50 to 150	Rough: 0005 Finish: .0002 max.	1/3 1/6	C60KV
			25 to 30	15 to 46	Rough: .013 Finish: .005 max.	1/3 1/6	C60KV
51. MAGNETIC ALLOYS Magnetic Core Iron (up to 4% Si)	185 to 240	Wrought	5000 to 6500	75 to 200	Rough: .001 Finish: .0002 max.	1/3 1/6	A60LV
			25 to 33	23 to 60	Rough: .025 Finish: .005 max.	1/3 1/6	A60LV

Maximum hole length is 2.5 times hole diameter.
Maximum wheel width is 1.5 times wheel diameter.
See section 16 for Cutting Fluid Recommendations.
*Wheel recommendations are for wet grinding 0 8- to 2-inch [20 to 50 mm] diameter holes For LARGER holes—use the same or softer grade wheel. For SMALLER holes—use a harder grade wheel Also see section 20.2, Grinding Guidelines

†Use diamond wheel, see section 8.10.
‡Diamond wheel is preferable, see section 8.10

8.8 Internal Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
51. MAGNETIC ALLOYS (cont.) Hi Perm 49 HyMu 80	185 to 240	Wrought	5000 to 6000	50 to 150	Rough. 0005 Finish .0002 max.	1/3 1/6	C60KV
			25 to 30	15 to 46	Rough: .013 Finish: .005 max.	1/3 1/6	C60KV
Alnico I Alnico II Alnico III Alnico IV Alnico V Alnico V-7 Alnico XII Columax-5 Hyflux Alnico V-7	45 R_C to 58 R_C	As Cast	5000 to 6000	50 to 150	Rough. .0005 Finish: .0002 max.	1/3 1/6	A60JV
			25 to 30	15 to 46	Rough: .013 Finish: .002 max.	1/3 1/6	A60JV
52. FREE MACHINING CONTROLLED EXPANSION ALLOYS Invar 36	125 to 220	Annealed or Cold Drawn	5000 to 6000	50 to 150	Rough: .0005 Finish. .0002 max.	1/3 1/6	C60KV
			25 to 30	15 to 46	Rough: .013 Finish: .005 max.	1/3 1/6	C60KV
53. CONTROLLED EXPANSION ALLOYS Invar Kovar	125 to 250	Annealed or Cold Drawn	5000 to 6000	50 to 150	Rough: .0005 Finish. .0002 max.	1/3 1/6	C60KV
			25 to 30	15 to 46	Rough: .013 Finish: .005 max.	1/3 1/6	C60KV
54. CARBONS & GRAPHITES Mechanical Grades	40 to 100 Shore	Molded or Extruded	5000 to 6500	50	Rough. .0005 Finish .0002 max.	1/3 1/6	C36KV
			25 to 33	15	Rough: .013 Finish: .005 max.	1/3 1/6	C36KV
Brush Grade Carbon	8 to 90 Shore	Molded or Extruded	5000 to 6500	50	Rough: .0005 Finish .0002 max.	1/3 1/6	C36KV
			25 to 45	15 to [illegible]	Rough: .013 Finish: .005 max.	1/3 1/6	C36KV

Maximum hole length is 2 5 times hole diameter.
Maximum wheel width is 1.5 times wheel diameter
See section 16 for Cutting Fluid Recommendations.
*Wheel recommendations are for wet grinding 0 8- to 2-inch [20 to 50 mm] diameter holes. For LARGER holes—use the same or softer grade wheel For SMALLER holes—use a harder grade wheel. Also see section 20 2, Grinding Guidelines.

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
Graphite	—	—	5000 to 6500	50	Rough· 0005 Finish· 0002 max	1/3 1/6	Rough C36IV Finish. C60IV
			25 to 33	15	Rough: .013 Finish: .005 max.	1/3 1/6	Rough: C36IV Finish: C60IV
55. GLASSES & CERAMICS Glass	480 to 530 Knoop 100g	—	5000 to 6500	50 to 150	Rough· .0005 Finish· 0002 max	1/3 1/6	C80JV
			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Porcelain Enamel	—	—	5000 to 6500	50 to 150	Rough· .0005 Finish· 0002 max.	1/3 1/6	C60KV
			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Ceramics Alumina (Aluminum Oxide) Alumina-Mullite Aluminum Silicate Beryllia (Beryllium Oxide)†† Magnesia (Magnesium Oxide) Mullite Silicon Carbide Silicon Nitride Thoria (Thorium Oxide)†† Titania (Titanium Oxide) Titanium Diboride†† Zircon (Zirconium Silicate) Zirconia (Zirconium Oxide)	Over 800 Knoop	Fired	5000 to 6500	50 to 100	Rough: .0005 Finish: .0002 max.	1/3 1/6	Rough: C46JV‡ Finish: C60JV‡
			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
56. PLASTICS **Thermoplastics**	—	Cast, Molded, Extruded, or Filled and Molded	5000 to 6500	50 to 150	Rough: .001 Finish: .0005 max.	1/3 1/6	A60KV
			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Maximum hole length is 2.5 times hole diameter.
Maximum wheel width is 1.5 times wheel diameter.
See section 16 for Cutting Fluid Recommendations.
*Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter holes. For LARGER holes—use the same or softer grade wheel. For SMALLER holes—use a harder grade wheel Also see section 20 2, Grinding Guidelines

‡Diamond wheel is preferable, see section 8 10
††CAUTION. Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions

8.8 Internal Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
56. PLASTICS (cont.)							
Thermosetting Plastics	—	Cast	5000 to 6500	50 to 150	Rough: .001 Finish: .0005 max.	1/3 1/6	C46IV
			25 to 33	15 to 46	Rough: .025 Finish: .013 max.	1/3 1/6	C46IV
	—	Molded	5000 to 6500	50 to 150	Rough: 001 Finish. 0005 max.	1/3 1/6	C46KV
			25 to 33	15 to 46	Rough: .025 Finish: .013 max.	1/3 1/6	C46KV
	—	Laminated	5000 to 6500	50 to 150	Rough, .001 Finish: .0005 max.	1/3 1/6	C36LV
			25 to 33	15 to 46	Rough: .025 Finish: .013 max.	1/3 1/6	C36LV
58. FLAME (THERMAL) SPRAYED MATERIALS							
Sprayed Carbides	—	—	5500 to 6500	50 to 100	Rough: .0005 Finish: .0002 max.	1/3 1/6	C80HV§
Chromium Carbide							
Chromium Carbide-Cobalt Blend							
Columbium Carbide							
Tantalum Carbide							
Titanium Carbide							
Tungsten Carbide							
Tungsten Carbide-Cobalt							
Tungsten Carbide (Cobalt)-Nickel Alloy Blend			28 to 33	15 to 30	Rough: .013 Finish: .005 max.	1/3 1/6	C80HV§

Maximum hole length is 2.5 times hole diameter.
Maximum wheel width is 1.5 times wheel diameter.
See section 16 for Cutting Fluid Recommendations.

*Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter holes. For LARGER holes—use the same or softer grade wheel. For SMALLER holes—use a harder grade wheel. Also see section 20.2, Grinding Guidelines.

§Diamond wheel is preferable for flame sprayed carbides and ceramics, see section 8.10.

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFICATION* ANSI ISO
Inorganic Coating Materials					Rough		
Alumina (Pure)			5500	50	.0005	1/3	
Alumina (Grey) containing Titania			to	to			C60IV§
Alumina, Nickel-Aluminide Blends			6500	100	Finish		
Barium Titanate	—	—			.0002 max	1/6	
Boron††					Rough:		
Calcium Titanate			28	15	.013	1/3	
Calcium Zirconate			to	to			C80IV§
Chromium Disilicide††			33	30	Finish:		
Chromium Oxide††					.005 max	1/6	
Cobalt (40%), Zirconia Blend							
Columbium (Niobium)††							
Glass (Kovar sealing)††							
Hexaboron Silicide††							
Magnesia Alumina Spinel							
Magnesium Zirconate							
Molybdenum Disilicide							
Mullite							
Nickel (40%), Alumina Blend							
Nickel Oxide							
Rare Earth Oxides							
Tantalum							
Titania (50%), Alumina Blend							
Titanium Oxide							
Tungsten							
Yttrium Zirconate							
Zirconia (Lime Stabilized)							
Zirconia, Nickel-Aluminide Blends							
Zirconium Oxide (Hafnia Free, Lime Stabilized)							
Zirconium Silicate							
Sprayed Metals (Group I)					Rough:		
Co-Cr-B Alloy (Self Fluxing)			5500	50	.0005	1/3	
Ni-Cr-B Alloy (Self Fluxing)			to	to			C60JV
Nickel Chrome Steel (Special)			6500	150	Finish:		
Stainless Steel	—	—			.0002 max.	1/6	
					Rough:		
			28	15	.013	1/3	
			to	to			C80JV
			33	46	Finish:		
					.005 max.	1/6	
Sprayed Metals (Group II)					Rough:		
Bronze			5500	50	.0005	1/3	
Chromium			to	to			C80KV
Cobalt			6500	150	Finish:		
Nickel	—	—			.0002 max.	1/6	
Molybdenum					Rough:		
Monel			28	15	.013	1/3	
			to	to			C80KV
			33	46	Finish:		
					.005 max.	1/6	
Sprayed Metals (Group III)					Rough:		
Carbon Steel			5500	50	.0005	1/3	
Iron			to	to			C60LV
Precipitation Hardening Steel			6500	150	Finish:		
	—	—			.0002 max.	1/6	
					Rough:		
			28	15	.013	1/3	
			to	to			C80LV
			33	46	Finish:		
					.005 max.	1/6	

Maximum hole length is 2.5 times hole diameter.
Maximum wheel width is 1.5 times wheel diameter.
See section 16 for Cutting Fluid Recommendations
*Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter holes. For LARGER holes—use the same or softer grade wheel. For SMALLER holes—use a harder grade wheel. Also see section 20.2, Grinding Guidelines.

§Diamond wheel is preferable for flame sprayed carbides and ceramics; see section 8.10.
††CAUTION: Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions.

8.8 Internal Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION* ANSI ISO
59. PLATED MATERIALS Chromium Plate	—	—	3000 to 4000	50 to 150	Rough 0005 Finish. .0002 max	1/3 1/6	A80HV
			15 to 20	15 to 46	Rough: .013 Finish: .005 max.	1/3 1/6	A80HV
Nickel Plate Silver Plate	—	—	5000 to 6500	50 to 150	Rough: 0005 Finish: .0002 max.	1/3 1/6	A60KV
			25 to 33	15 to 46	Rough: .013 Finish: .005 max.	1/3 1/6	A60KV
61. RUBBER	Soft	—	5000 to 6500	50 to 150	Rough: 001 Finish: .0005 max.	1/3 1/6	C30IV
			25 to 33	15 to 46	Rough: .025 Finish: .013 max.	1/3 1/6	C30IV
	Hard	—	5000 to 6500	50 to 150	Rough: .001 Finish: .0005 max.	1/3 1/6	C36JV
			25 to 33	15 to 46	Rough: .025 Finish: .013 max.	1/3 1/6	C36JV

Maximum hole length is 2.5 times hole diameter.
Maximum wheel width is 1.5 times wheel diameter.
See section 16 for Cutting Fluid Recommendations
*Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter holes. For LARGER holes—use the same or softer grade wheel. For SMALLER holes—use a harder grade wheel. Also see section 20.2, Grinding Guidelines.

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION ANSI ANSI
1. FREE MACHINING CARBON STEELS, WROUGHT **Low Carbon Resulfurized** 1108 1118 1109 1119 1110 1211 1115 1212 1116 1213 1117 1215 **Medium Carbon Resulfurized** 1132 1140 1145 1137 1141 1146 1139 1144 1151 **Low Carbon Leaded** 10L18 12L13 12L15 11L17 12L14 **Medium Carbon Leaded** 10L45 11L37 11L44 10L50 11L41	Over 50 Rc	Carburized and/or Quenched and Tempered	5,000 to 10,000	80 to 150	Rough: 0005 Finish. 0002 max.	1/3 1/8	B120TB B180TV
			25 to 51	24 to 46	Rough: .013 Finish: .005 max.	1/3 1/8	B120TB B180TV
2. CARBON STEELS, WROUGHT **Low Carbon** 1005 1012 1019 1026 1006 1013 1020 1029 1008 1015 1021 1513 1009 1016 1022 1518 1010 1017 1023 1522 1011 1018 1025 **Medium Carbon** 1030 1042 1053 1541 1033 1043 1055 1547 1035 1044 1524 1548 1037 1045 1525 1551 1038 1046 1526 1552 1039 1049 1527 1040 1050 1536 **High Carbon** 1060 1074 1085 1566 1064 1075 1086 1572 1065 1078 1090 1069 1080 1095 1070 1084 1561	Over 50 Rc	Carburized and/or Quenched and Tempered	5,000 to 10,000	80 to 150	Rough .0005 Finish. 0002 max	1/3 1/8	B120TB B180TV
			25 to 51	24 to 46	Rough: .013 Finish: .005 max.	1/3 1/8	B120TB B180TV

See section 16 for Cutting Fluid Recommendations
See section 20.1 for additional information.

8.9 Internal Grinding

Cubic Boron Nitride Wheels

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION ANSI ANSI
4. FREE MACHINING ALLOY STEELS, WROUGHT **Medium Carbon Resulfurized** 4140 4140Se 4142Te 4145Se 4147Te 4150 **Medium and High Carbon Leaded** 41L30 41L47 51L32 86L40 41L40 41L50 52L100 41L45 43L40 86L20	Over 50 Rc	Carburized and/or Quenched and Tempered	5,000 to 10,000 25 to 51	80 to 1[illegible] 24 to 46	Rough 0005 Finish .0002 max. Rough: .013 Finish: .005 max.	1/3 1/8 1/3 1/8	B120TB B180TV T120TB T180TV
5. ALLOY STEELS, WROUGHT **Low Carbon** 4012 4615 4817 8617 4023 4617 4820 8620 4024 4620 5015 8622 4118 4621 5115 8822 4320 4718 5120 9310 4419 4720 6118 94B15 4422 4815 8115 94B17 **Medium Carbon** 1330 4145 5132 8640 1335 4147 5135 8642 1340 4150 5140 8645 1345 4161 5145 86B45 4027 4340 5147 8650 4028 4427 5150 8655 4032 4626 5155 8660 4037 50B40 5160 8740 4042 50B44 51B60 8742 4047 5046 6150 9254 4130 50B46 81B45 9255 4135 50B50 8625 9260 4137 5060 8627 94B30 4140 50B60 8630 4142 5130 8637 **High Carbon** 50100 51100 52100 M-50	Over 50 Rc	Carburized and/or Quenched and Tempered	5,000 to 10,000 25 to 51	80 to 150 24 to 46	Rough: .0005 Finish: .0002 max. Rough: .013 Finish: .005 max.	1/3 1/8 1/3 1/8	B120TB B180TV B120TB B180TV

See section 16 for Cutting Fluid Recommendations
See section 20.1 for additional information

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION ANSI ANSI
6. HIGH STRENGTH STEELS, WROUGHT 300M H11 4330V H13 4340 HP 9-4-20 4340Si HP 9-4-25 98BV40 HP 9-4-30 D6ac HP 9-4-45	Over 50 R_c	Quenched and Tempered	5,000 to 10,000	80 to 150	Rough .0005 Finish .0002 max.	1/3 1/8	B120TB B180TV
			25 to 51	24 to 46	Rough: .013 Finish: .005 max.	1/3 1/8	B120TB B180TV
7. MARAGING STEELS, WROUGHT 120 Grade 180 Grade 200 Grade 250 Grade 300 Grade 350 Grade HY220 ASTM A538 Grades A, B, C	Over 50 R_c	Maraged	5,000 to 10,000	80 to 150	Rough .0005 Finish: .0002 max	1/3 1/8	B120TB B180TV
			25 to 51	24 to 46	Rough: .013 Finish: .005 max.	1/3 1/8	B120TB B180TV
8. TOOL STEELS, WROUGHT A2 H14 M10 P20 A3 H19 M30 P21 A4 H21 M33 S1 A6 H22 M34 S2 A7 H23 M36 S5 A8 H24 M41 S6 A9 H25 M42 S7 A10 H26 M43 T1 D2 H42 M44 T2 D3 L2 M46 T4 D4 L6 M47 T5 D5 L7 O1 T6 D7 M1 O2 T8 F1 M2 O6 T15 F2 M3-1 O7 W1 H10 M3-2 P2 W2 H11 M4 P4 W5 H12 M6 P5 H13 M7 P6 SAE J438b Types W108, W109, W110, W112, W209, W210, W310	Over 50 R_c	Quenched and Tempered	5,000 to 10,000	80 to 150	Rough: .0005 Finish: 0002 max.	1/3 1/8	B120TB B180TV
			25 to 51	24 to 46	Rough: .013 Finish: .005 max.	1/3 1/8	B120TB B180TV

See section 16 for Cutting Fluid Recommendations
See section 20.1 for additional information

8.9 Internal Grinding

Cubic Boron Nitride Wheels

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION ANSI ANSI
9. NITRIDING STEELS, WROUGHT Nitralloy 125 Nitralloy 135 Nitralloy 135 Mod Nitralloy 225 Nitralloy 230 Nitralloy EZ Nitralloy N Nitrex 1	60 R_c to 65 R_c	Nitrided	5,000 to 10,000	80 to 150	Rough 0005 Finish 0002 max	1/3 1/8	B120TB B180TV
			25 to 51	24 to 46	Rough .013 Finish .005 max.	1/3 1/8	B120TB B180TV
13. STAINLESS STEELS, WROUGHT **Martensitic** 403 440A 410 440B 414 440C 420 501 422 502 431 Greek Ascoloy	Over 275	Quenched and Tempered	5,000 to 10,000	80 to 150	Rough 0005 Finish 0002 max.	1/3 1/8	B120TB B180TV
			25 to 51	24 to 46	Rough .013 Finish .005 max.	1/3 1/8	B120TB B180TV
15. CARBON STEELS, CAST **Low Carbon** ASTM A426 Grade CP1 1010 1020 **Medium Carbon** ASTM A352. Grades LCA, LCB, LCC ASTM A356 Grade 1 1030 1040 1050	Over 50 R_c	Carburized and/or Quenched and Tempered	5,000 to 10,000	80 to 150	Rough .0005 Finish 0002 max.	1/3 1/8	B120TB B180TV
			25 to 51	24 to 46	Rough .013 Finish .005 max.	1/3 1/8	B120TB B180TV

See section 16 for Cutting Fluid Recommendations
See section 20 1 for additional information

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION ANSI ANSI
16. ALLOY STEELS, CAST **Low Carbon** ASTM A217 Grade WC9 ASTM A352 Grades LC3, LC4 ASTM A426 Grades CP2, CP5, CP5b, CP11, CP12, CP15, CP21, CP22 1320 2320 4120 8020 2315 4110 4320 8620 **Medium Carbon** ASTM A27 Grades N1, N2, U-60-30, 60-30, 65-35, 70-36, 70-40 ASTM A148 Grades 80-40, 80-50, 90-60, 105-85, 120-95, 150-125, 175-145 ASTM A216 Grades WCA, WCB, WCC ASTM A217 Grades WC1, WC4, WC5, WC6 ASTM A352 Grades LC1, LC2, LC2-1 ASTM A356 Grades 2, 5, 6, 8, 9, 10 ASTM A389 Grades C23, C24 ASTM A486 Classes 70, 90, 120 ASTM A487 Classes 1N, 2N, 4N, 6N, 8N, 9N, 10N, DN, 1Q, 2Q, 4Q, 4QA, 6Q, 7Q, 8Q, 9Q, 10Q 1330 4130 80B30 8640 1340 4140 8040 9525 2325 4330 8430 9530 2330 4340 8440 9535 4125 8030 8630	Over 50 R_C	Carburized and/or Quenched and Tempered	5,000 to 10,000 25 to 51	80 to 150 24 to 46	Rough 0005 Finish 0002 max Rough .013 Finish .005 max	1/3 1/8 1/3 1/8	B120TB B180TV B120TB B180TV
17. TOOL STEELS, CAST ASTM A597 Grades CA-2, CD-2, CD-5, CH-12, CH-13, CO-1, CS-5	Over 50 R_C	Quenched and Tempered	5,000 to 10,000	80 to 150	Rough 0005 Finish 0002 max	1/3 1/8	B120TB B180TV

See section 16 for Cutting Fluid Recommendations
See section 20 1 for additional information

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MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm / m/s	WORK SPEED fpm / m/min	INFEED on dia. in/pass / mm/pass	TRAVERSE Wheel widtn per rev. of work	WHEEL IDENTIFI-CATION ANSI / ANSI
48. MACHINABLE CARBIDES Ferro-Tic	68 R_C to 72 R_C	Hardened and Tempered	1200 to 1500	30 to 50	Rough 001	3	ASD100-R100-B*
					Finish 0003 max	6	ASD150-R100-B*
			6 to 7.5	9 to 15	Rough .025	3	ASD100-R100-B*
					Finish .008 max.	6	ASD150-R100-B*
49. CARBIDES Titanium Carbide Tungsten Carbide	89 R_A to 94 R_A	—	5000 to 6000	50 to 100	Rough 001	3	D150-R75-B
					Finish .0002 max	6	D220-R75-B
			25 to 30	15 to 30	Rough .025	3	D150-R75-B
					Finish .005 max.	6	D220-R75-B
51. MAGNETIC ALLOYS Magnetic Core Iron (up to 4% Si) Hi Perm 49 HyMu 80	185 to 240	Wrought	5000 to 6000	50 to 60	Rough 003	3	D100-N100-M
					Finish: .001 max	6	D220-N100-M
			25 to 30	15 to 18	Rough: .075	3	D100-N100-M
					Finish: .025 max.	6	D220-N100-M
Alnico I Alnico II Alnico III Alnico IV Alnico V Alnico V-7 Alnico XII Columax-5 Hyflux Alnico V-7	45 R_C to 58 R_C	As Cast	5000 to 6000	30 to 40	Rough .003	3	D100-N75-M
					Finish .001 max	6	D220-N75-M
			25 to 30	9 to 12	Rough: .075	3	D100-N75-M
					Finish .025 max.	6	D220-N75-M
55. GLASSES & CERAMICS Machinable Glass-Ceramic (MACOR)	250 Knoop 100g	Cast	5000 to 5500	50 to 100	Rough 003	3	D100-N100-M
					Finish 001 max.	6	D120-N100-M
			25 to 28	15 to 30	Rough: .075	3	D100-N100-M
					Finish .025 max.	6	D120-N100-M
PYROCERAM	700 Knoop 100g	—	4000 to 4500	50 to 100	Rough: .001	3	D100-N100-M
					Finish .0002 max.	6	D220-N100-M
			20 to 23	15 to 30	Rough .025	3	D100-N100-M
					Finish .005 max.	6	D220-N100-M

See section 16 for Cutting Fluid Recommendations
See section 20.1 for additional information

*Metal-coated diamond

8.10 Internal Grinding
Diamond Wheels

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min	INFEED on dia. in/pass mm/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION ANSI ANSI
55. GLASSES & CERAMICS (cont.)							
Glass	480 to 530 Knoop 100g	—	4000 to 4500	50 to 100	Rough: .001	3	D100-R50-M
					Finish: .0002 max.	6	D220-R50-M
			20 to 23	15 to 30	Rough: .025	3	D100-R50-M
					Finish: .005 max.	6	D220-R50-M
Mica	—	—	5000 to 6000	50 to 150	Rough: 003	3	D100-N75-B
					Finish: .001 max.	6	D220-N75-B
			25 to 40	15 to 30	Rough: .075	3	D100-N75-B
					Finish: .025 max.	6	D220-N75-B
Porcelain Enamel	—	—	4000 to 4500	50 to 100	Rough .001	3	D100-R100-M
					Finish: .0005 max.	6	D220-R100-M
			20 to 23	15 to 30	Rough: .025	3	D100-R100-M
					Finish: .013 max.	6	D220-R100-M
Ceramics							
Alumina (Aluminum Oxide)			4000 to 4500	50 to 100	Rough. .002	3	D80-N100-M
Alumina-Mullite							
Aluminum Silicate	Over 800 Knoop	Fired			Finish: .0005 max	6	D100-N100-M
Beryllia (Beryllium Oxide)††							
Magnesia (Magnesium Oxide)							
Mullite							
Silicon Carbide							
Silicon Nitride							
Thoria (Thorium Oxide)††							
Titania (Titanium Oxide)							
Titanium Diboride††							
Zircon (Zirconium Silicate)							
Zirconia (Zirconium Oxide)			20 to 23	15 to 30	Rough: .050	3	D80-N100-M
					Finish: .013 max.	6	D100-N100-M

See section 16 for Cutting Fluid Recommendations
See section 20 1 for additional information

††CAUTION: Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm	WORK SPEED fpm	INFEED on dia. in/pass	TRAVERSE Wheel width per rev. of work	WHEEL IDENTIFI-CATION ANSI
58. FLAME (THERMAL) SPRAYED MATERIALS							
Sprayed Carbides			5000 to 6000	50 to 100	Rough .002	3	D150-N100-B
Chromium Carbide					Finish .0005 max	6	D220-N100-B
Chromium Carbide-Cobalt Blend	—	—					
Columbium Carbide					Rough .050	3	D150-N100-B
Tantalum Carbide							
Titanium Carbide					Finish .013 max.	6	D220-N100-B
Tungsten Carbide							
Tungsten Carbide-Cobalt							
Tungsten Carbide (Cobalt)-Nickel Alloy Blend							
Inorganic Coating Materials			5000 to 6000	50 to 100	Rough: .002	3	D120-N100-B
Alumina (Pure)					Finish: .0005 max.	6	D220-N100-B
Alumina (Grey) containing Titania							
Alumina, Nickel-Aluminide Blends	—	—					
Barium Titanate							
Boron††							
Calcium Titanate							
Calcium Zirconate							
Chromium Disilicide††							
Chromium Oxide††							
Cobalt (40%), Zirconia Blend							
Columbium (Niobium)††							
Glass (Kovar sealing)††							
Hexaboron Silicide††							
Magnesia Alumina Spinel							
Magnesium Zirconate							
Molybdenum Disilicide							
Mullite							
Nickel (40%), Alumina Blend							
Nickel Oxide							
Rare Earth Oxides							
Tantalum							
Titania (50%), Alumina Blend							
Titanium Oxide							
Tungsten							
Yttrium Zirconate							
Zirconia (Lime Stabilized)							
Zirconia, Nickel-Aluminide Blends							
Zirconium Oxide (Hafnia Free, Lime Stabilized)							
Zirconium Silicate							

See section 16 for Cutting Fluid Recommendations
See section 20.1 for additional information

†† CAUTION: Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions

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MATERIAL	HARD-NESS Btn	CONDITION	WHEEL SPEED fpm m/s	THRUFEED OF WORK* in/min m/min	INFEED on dia. in pass mm/pass	WHEEL IDENTIFI-CATION† ANSI ISO
1. FREE MACHINING CARBON STEELS, WROUGHT **Low Carbon Resulfurized** 1108 1118 1109 1119 1110 1211 1115 1212 1116 1213 1117 1215 **Medium Carbon Resulfurized** 1132 1140 1145 1137 1141 1146 1139 1144 1151 **Low Carbon Leaded** 10L18 12L13 12L15 11L17 12L14 **Medium Carbon Leaded** 10L45 11L37 11L44 10L50 11L41	50 R_C max	Hot Rolled, Normalized Annealed, Cold Drawn or Quenched and Tempered	5500 to 6500 28 to 33	50 to 150 1.3 to 3.8	Rough .005 Finish .0015 max Rough: .13 Finish: .038 max	A60MV A60MV
	Over 50 R_C	Carburized and/or Quenched and Tempered	5500 to 6500 28 to 33	50 to 150 1.3 to 3.8	Rough .005 Finish .0015 max Rough: .13 Finish: .038 max	A60LV A60LV
2. CARBON STEELS, WROUGHT **Low Carbon** 1005 1012 1019 1026 1006 1013 1020 1029 1008 1015 1021 1513 1009 1016 1022 1518 1010 1017 1023 1522 1011 1018 1025 **Medium Carbon** 1030 1042 1053 1541 1033 1043 1055 1547 1035 1044 1524 1548 1037 1045 1525 1551 1038 1046 1526 1552 1039 1049 1527 1040 1050 1536 **High Carbon** 1060 1074 1085 1566 1064 1075 1086 1572 1065 1078 1090 1069 1080 1095 1070 1084 1561	50 R_C max	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	5500 to 6500 28 to 33	50 to 150 1.3 to 3.8	Rough .005 Finish .0015 max. Rough: .13 Finish: .038 max.	A60MV A60MV
	Over 50 R_C	Carburized and/or Quenched and Tempered	5500 to 6500 28 to 33	50 to 150 1.3 to 3.8	Rough. .005 Finish .0015 max Rough: .13 Finish: .038 max	A60LV A60LV
3. CARBON AND FERRITIC ALLOY STEELS (HIGH TEMPERATURE SERVICE) ASTM A369 Grades FPA, FPB, FP1, FP2, FP3b, FP5, FP7, FP9, FP11, FP12, FP21, FP22	150 to 200	As Forged, Annealed or Normalized and Tempered	5500 to 6500 28 to 33	50 to 150 1.3 to 3.8	Rough .005 Finish .0015 max Rough: .13 Finish: .038 max	A60MV A60MV

See section 16 for Cutting Fluid Recommendations

*See section 8.12 for Work Traverse Rates. As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm

†Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter work. For LARGER diameter work—use a softer grade and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Also see section 20.2, Grinding Guidelines

8.11 Centerless Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	THRUFEED OF WORK* in/min m/min	INFEED on dia. in/pass mm/pass	WHEEL IDENTIFI-CATION† ANSI ISO
4. FREE MACHINING ALLOY STEELS, WROUGHT **Medium Carbon Resulfurized** 4140 4140Se 4142Te 4145Se 4147Te 4150 **Medium and High Carbon Leaded** 41L30 41L47 51L32 86L40 41L40 41L50 52L100 41L45 43L40 86L20	50 R_C max	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	5500 to 6500	50 to 150	Rough: .005 Finish 0015 max.	A60MV
	Over 50 R_C	Carburized and/or Quenched and Tempered	5500 to 6500	50 to 100	Rough: .005 Finish 0015 max.	A80LV
5. ALLOY STEELS, WROUGHT **Low Carbon** 4012 4615 4817 8617 4023 4617 4820 8620 4024 4620 5015 8622 4118 4621 5115 8822 4320 4718 5120 9310 4419 4720 6118 94B15 4422 4815 8115 94B17 **Medium Carbon** 1330 4145 5132 8640 1335 4147 5135 8642 1340 4150 5140 8645 1345 4161 5145 86B45 4027 4340 5147 8650 4028 4427 5150 8655 4032 4626 5155 8660 4037 50B40 5160 8740 4042 50B44 51B60 8742 4047 5046 6150 9254 4130 50B46 81B45 9255 4135 50B50 8625 9260 4137 5060 8627 94B30 4140 50B60 8630 4142 5130 8637 **High Carbon** 50100 51100 52100 M-50	50 R_C max.	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	5500 to 6500	50 to 150	Rough. .005 Finish .0015 max.	A60MV
	Over 50 R_C	Carburized and/or Quenched and Tempered	4000 to 6000	50 to 150	Rough: .005 Finish: .0015 max.	A80LV

See section 16 for Cutting Fluid Recommendations

*See section 8.12 for Work Traverse Rates As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm

†Wheel recommendations are for wet grinding 0 8- to 2-inch [20 to 50 mm] diameter work. For LARGER diameter work—use a softer grade and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel Also see section 20.2, Grinding Guidelines

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm / m/s	THRUFEED OF WORK* in/min / m/min	INFEED on dia. in/pass / mm/pass	WHEEL IDENTIFI-CATION† ANSI / ISO
6. HIGH STRENGTH STEELS, WROUGHT 300M 4330V 4340 4340Si 98BV40 D6ac H11 H13 HP 9-4-20 HP 9-4-25 HP 9-4-30 HP 9-4-45	50 R_C max	Annealed, Normalized or Quenched and Tempered	5500 to 6500	50 to 150	Rough 005 Finish 0015 max	A60MV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	A60MV
	Over 50 R_C	Quenched and Tempered	4000 to 6000	50 to 150	Rough: 003 Finish. .001 max.	A80KV
			20 to 30	1.3 to 3.8	Rough: .075 Finish: .025 max.	A80KV
7. MARAGING STEELS, WROUGHT ASTM A538 Grades A, B, C 120 Grade 180 Grade 200 Grade 250 Grade 300 Grade 350 Grade HY230	50 R_C max.	Annealed or Maraged	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max	A60MV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	A60MV
	Over 50 R_C	Maraged	4000 to 6000	50 to 150	Rough: .003 Finish: .001 max.	A80KV
			20 to 30	1.3 to 3.8	Rough: .075 Finish: .025 max.	A80KV
8. TOOL STEELS, WROUGHT **Group I** A2 H13 L6 P20 A3 H14 L7 P21 A4 H19 O1 S1 A6 H21 O2 S2 A8 H22 O6 S5 A9 H23 O7 S6 A10 H24 P2 S7 H10 H25 P4 W1 H11 H26 P5 W2 H12 L2 P6 W5 SAE J438b: Types W108, W109, W110, W112, W209, W210, W310	50 R_C max	Annealed or Quenched and Tempered	5500 to 6500	50 to 150	Rough. 005 Finish .0015 max.	A60MV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	A60MV
	Over 50 R_C	Quenched and Tempered	4000 to 6000	50 to 150	Rough. .005 Finish: .0015 max.	A60LV
			20 to 30	1.3 to 3.8	Rough: .13 Finish: .038 max.	A60LV

See section 16 for Cutting Fluid Recommendations

*See section 8.12 for Work Traverse Rates. As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm

†Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter work. For LARGER diameter work—use a softer grade and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Also see section 20.2, Grinding Guidelines

8.11 Centerless Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm / m/s	THRUFEED OF WORK* in/min / m/min	INFEED on dia. in/pass / mm/pass	WHEEL IDENTIFI-CATION† ANSI / ISO
8. TOOL STEELS, WROUGHT (cont.) **Group II** D2, D3, D4, D5, F1, F2, H42, M1, M2, M3-1, M10, M30, M42, T1, T2, T4, T8	50 R_C max	Annealed or Quenched and Tempered	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max.	A60MV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	A60MV
	50 R_C to 58 R_C	Quenched and Tempered	4000 to 6000	50 to 150	Rough: .004 Finish. .001 max.	A60LV
			20 to 30	1.3 to 3.8	Rough: .102 Finish: .025 max.	A60LV
	Over 58 R_C	Quenched and Tempered	4000 to 6000	50 to 150	Rough: .003 Finish: .001 max.	A80KV
			20 to 30	1.3 to 3.8	Rough: .075 Finish: .025 max.	A80KV
Group III A7, D7, M3-2, M6, M7, M33, M34, M36, M41, M43, M44, M46, M47, T5, T6	50 R_C max	Annealed or Quenched and Tempered	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max.	A60LV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	A60LV
	50 R_C to 58 R_C	Quenched and Tempered	4000 to 6000	50 to 150	Rough: .004 Finish: .001 max.	A80KV
			20 to 30	1.3 to 3.8	Rough: .102 Finish: .025 max.	A80KV
	Over 58 R_C	Quenched and Tempered	4000 to 5500	50 to 150	Rough: .003 Finish· .001 max.	A80JV
			20 to 28	1.3 to 3.8	Rough: .075 Finish: .025 max.	A80JV

See section 16 for Cutting Fluid Recommendations

*See section 8 12 for Work Traverse Rates As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm

†Wheel recommendations are for wet grinding 0 8- to 2-inch [20 to 50 mm] diameter work. For LARGER diameter work—use a softer grade and/or coarser grit wheel For SMALLER diameter work—use a harder grade wheel Also see section 20.2, Grinding Guidelines

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm / m/s	THRUFEED OF WORK* in/min / m/min	INFEED on dia. in/pass / mm/pass	WHEEL IDENTIFI-CATION† ANSI / ISO
Group IV M4 T15	50 R_C max	Annealed or Quenched and Tempered	4000 to 6000	50 to 150	Rough: .004 Finish: .001 max.	A60KV
			20 to 30	1.3 to 3.8	Rough: .102 Finish: .025 max.	A60KV
	50 R_C to 58 R_C	Quenched and Tempered	4000 to 5500	50 to 150	Rough: .003 Finish: .001 max	A80JV
			20 to 28	1.3 to 3.8	Rough: .075 Finish: .025 max.	A80JV
	Over 58 R_C	Quenched and Tempered	4000 to 5500	50 to 150	Rough: .002 Finish: .001 max	A80IV
			20 to 28	1.3 to 3.8	Rough: .050 Finish: .025 max.	A80IV
9. NITRIDING STEELS, WROUGHT Nitralloy 125 Nitralloy 135 Nitralloy 135 Mod. Nitralloy 225 Nitralloy 230 Nitralloy EZ Nitralloy N Nitrex 1	200 to 350	Annealed, Normalized or Quenched and Tempered	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max.	A60LV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	A60LV
	60 R_C to 65 R_C	Nitrided	4000 to 6000	50 to 150	Rough: .003 Finish: .001 max.	A80JV
			20 to 30	1.3 to 3.8	Rough: .075 Finish: .025 max.	A80JV
12. FREE MACHINING STAINLESS STEELS, WROUGHT **Ferritic** 430F 430F Se	135 to 185	Annealed	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max	A60LV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	A60LV

See section 18 for Cutting Fluid Recommendations

*See section 8.12 for Work Traverse Rates. As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm

†Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter work. For LARGER diameter work—use a softer grade and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Also see section 20.2, Grinding Guidelines

8.11 Centerless Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm / m/s	THRUFEED OF WORK* in/min / m/min	INFEED on dia. in pass / mm/pass	WHEEL IDENTIFI-CATION† ANSI / ISO
12. FREE MACHINING STAINLESS STEELS, WROUGHT (cont.)						
Austenitic						
203EZ 303 303MA 303Pb 303 Plus X 303Se	135 to 275	Annealed or Cold Drawn	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max.	C60LV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	C60LV
Martensitic						
416 416 Plus X 416Se 420F 420F Se 440F 440F Se	135 to 240	Annealed or Cold Drawn	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max.	A60LV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	A60LV
	Over 275	Quenched and Tempered	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max.	A60KV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	A60KV
13. STAINLESS STEELS, WROUGHT						
Ferritic						
405 409 429 430 434 436 442 446	135 to 185	Annealed	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max.	A60LV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	A60LV
Austenitic						
201 202 301 302 302B 304 304L 305 308 309 309S 310 310S 314 316 316L 317 321 330 347 348 384 385	135 to 275	Annealed or Cold Drawn	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max.	C60LV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	C60LV
Austenitic						
Nitronic 32 Nitronic 33 Nitronic 40 Nitronic 50 Nitronic 60	210 to 250	Annealed	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max.	C60LV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	C60LV

See section 15 for Cutting Fluid Recommendations

*See section 8.12 for Work Traverse Rates. As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm

†Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter work. For LARGER diameter work—use a softer grade and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Also see section 20.2, Grinding Guidelines.

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm	THRUFEED OF WORK* in/min	INFEED on dia. in/pass	WHEEL IDENTIFI-CATION† ANSI
13. STAINLESS STEELS, WROUGHT (cont.) **Austenitic (cont.)** (materials listed on preceding page)	325 to 375	Cold Drawn	5500 to 6500	50 to 100	Rough: 005 Finish: .0015 max.	C60KV
Martensitic 403 440A 410 440B 414 440C 420 501 422 502 431 Greek Ascoloy	135 to 275	Annealed	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max.	A60LV
	Over 275	Quenched and Tempered	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max.	A60KV
14. PRECIPITATION HARDENING STAINLESS STEELS, WROUGHT 15-5 PH 16-6 PH 17-4 PH 17-7 PH 17-14 Cu Mo AF-71 AFC-77 Almar 362 (AM-362) AM-350 AM-355 AM-363 Custom 450 Custom 455 HNM PH 13-8 Mo PH 14-8 Mo PH 15-7 Mo Stainless W	150 to 200	Solution Treated	5500 to 6500	50 to 150	Rough: 005 Finish: 0015 max.	A60LV
	275 to 440	Solution Treated & Hardened	5500 to 6500	50 to 150	Rough: .005 Finish .0015 max.	A60KV

See section 16 for Cutting Fluid Recommendations

*See section 8 12 for Work Traverse Rates. As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm.

†Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter work. For LARGER diameter work—use a softer grade and/or coarser grit wheel For SMALLER diameter work—use a harder grade wheel Also see section 20.2, Grinding Guidelines

8.11 Centerless Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	THRUFEED OF WORK* in/min m/min	INFEED on dia. in/pass mm/pass	WHEEL IDENTIFI-CATION† ANSI ISO
15. CARBON STEELS, CAST **Low Carbon** ASTM A426: Grade CP1 1010 1020 **Medium Carbon** ASTM A352: Grades LCA, LCB, LCC ASTM A356: Grade 1 1030 1040 1050	100 to 300	Annealed, Normalized, Normalized and Tempered, or Quenched and Tempered	5500 to 6500 28 to 33	50 to 150 1.3 to 3.8	Rough .005 Finish .0015 max Rough: .13 Finish: .038 max	A60MV A60MV
	Over 50 R_C	Carburized and/or Quenched and Tempered	5500 to 6500 28 to 33	50 to 150 1.3 to 3.8	Rough .005 Finish .0015 max Rough: .13 Finish: .038 max	A60LV A80LV
16. ALLOY STEELS, CAST **Low Carbon** ASTM A217: Grade WC9 ASTM A352: Grades LC3, LC4 ASTM A426: Grades CP2, CP5, CP5b, CP11, CP12, CP15, CP21, CP22 1320 4110 8020 2315 4120 8620 2320 4320 **Medium Carbon** ASTM A27: Grades N1, N2, U-60-30, 60-30 65-35, 70-36, 70-40 ASTM A148: Grades 80-40, 80-50, 90-60, 105-85, 120-95, 150-125, 175-145 ASTM A216: Grades WCA, WCB, WCC ASTM A217: Grades WC1, WC4, WC5, WC6 ASTM A352: Grades LC1, LC2, LC2-1 ASTM A356: Grades 2, 5, 6, 8, 9, 10 ASTM A389: Grades C23, C24 ASTM A486: Classes 70, 90, 120 ASTM A487: Classes 1N, 2N, 4N, 6N, 8N, 9N, 4Q, DN, 1Q, 2Q, 4Q, 4QA, 6Q, 7Q, 8Q, 9Q, 10Q 1330 4130 80B30 8640 1340 4140 8040 9525 2325 4330 8430 9530 2330 4340 8440 9535 4125 8030 8630	150 to 400	Annealed, Normalized, Normalized and Tempered, or Quenched and Tempered	5500 to 6500 28 to 33	50 to 150 1.3 to 3.8	Rough .005 Finish .0015 max. Rough: .13 Finish: .038 max.	A60MV A60MV
	Over 50 R_C	Carburized and/or Quenched and Tempered	4000 to 6000 20 to 30	50 to 150 1.3 to 3.8	Rough: 005 Finish: .0015 max Rough: .13 Finish: .038 max	A80LV A80LV
17. TOOL STEELS, CAST **Group I** ASTM A597. Grades CA-2, CH-12, CH-13, CO-1, CS-5	50 R_C max.	Annealed or Quenched and Tempered	5500 to 6500 28 to 33	50 to 150 1.3 to 3.8	Rough .005 Finish: .0015 max. Rough: .13 Finish: .038 max.	A60MV A60MV

See section 16 for Cutting Fluid Recommendations

*See section 8.12 for Work Traverse Rates. As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm

†Wheel recommendations are for wet grinding 0.8- to 2-inch (20 to 50 mm) diameter work. For LARGER diameter work—use a softer grade and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Also see section 20.2, Grinding Guidelines

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	THRUFEED OF WORK* in/min m/min	INFEED on dia. in/pass mm/pass	WHEEL IDENTIFI-CATION† ANSI ISO
17. TOOL STEELS, CAST (cont.) **Group I (cont.)** (materials listed on preceding page)	50 R_C to 58 R_C	Quenched and Tempered	4000 to 6000	50 to 150	Rough: .004 Finish: 001 max.	A60LV
			20 to 30	1.3 to 3.8	Rough: .102 Finish: .025 max.	A60LV
	Over 58 R_C	Quenched and Tempered	4000 to 6000	50 to 150	Rough: .003 Finish: .001 max	A60KV
			20 to 30	1.3 to 3.8	Rough: .075 Finish: .025 max.	A60KV
Group II ASTM A597 Grades CD-2, CD-5	200 to 250	Annealed	5500 to 6500	50 to 150	Rough: .005 Finish. 0015 max.	A60MV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	A60MV
	48 R_C to 56 R_C	Quenched and Tempered	4000 to 6000	50 to 150	Rough: .004 Finish .001 max.	A60LV
			20 to 30	1.3 to 3.8	Rough: .102 Finish: .025 max.	A60LV
	Over 56 R_C	Quenched and Tempered	4000 to 6000	50 to 150	Rough .003 Finish: .001 max.	A80KV
			20 to 30	1.3 to 3.8	Rough: .075 Finish: .025 max.	A80KV
18. STAINLESS STEELS, CAST **Ferritic** ASTM A217: Grades C5, C12 ASTM A296: Grades CB-30, CC-50, CE-30, CA6N, CA-6NM, CD4MCu ASTM A297: Grade HC ASTM A487: Class CA6NM ASTM A608: Grade HC30	135 to 185	Annealed	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max.	A60LV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	A60LV

See section 16 for Cutting Fluid Recommendations

*See section 8.12 for Work Traverse Rates. As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm.

†Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter work. For LARGER diameter work—use a softer grade and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Also see section 20.2, Grinding Guidelines.

8.11 Centerless Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm / m/s	THRUFEED OF WORK* in/min / m/min	INFEED on dia. in/pass / mm/pass	WHEEL IDENTIFI-CATION† ANSI / ISO
18. STAINLESS STEELS, CAST (cont.) **Austenitic** ASTM A296: Grades CF-3, CF-3M, CF-8, CF-8C, CF-8M, CF-16F, CF-20, CG-8M, CG-12, CH-20, CK-20, CN-7M, CN-7MS ASTM A297: Grades HD, HE, HF, HH, HI, HK, HL, HN, HP, HT, HU ASTM A351: Grades CF-3, CF-3A, CF-3M, CF-3MA, CF-8, CF-8A, CF-8C, CF-8M, CF-10MC, CH-8, CH-10, CH-20, CK-20, CN-7M, HK-30, HK-40, HT-30 ASTM A451: Grades CPF8A, CPF3, CPF3A, CPF3M, CPF8, CPF8C, CPF8C (Ta Max.), CPF8M, CPF10MC, CPH8, CPH10, CPH20, CPK20 ASTM A452: Grades TP 304H, TP 316H, TP 347H ASTM A608: Grades HD50, HE35, HF30, HH30, HH33, HI35, HK30, HK40, HL30, HL40, HN40, HT50, HU50	135 to 210	Annealed, Normalized or As Cast	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max.	C60LV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	C60LV
Martensitic ASTM A217: Grade CA-15 ASTM A296: Grades CA-15, CA-15M, CA-40 ASTM A426: Grades CP7, CP9, CPCA15 ASTM A487: Classes CA15a, CA-15M	135 to 225	Annealed, Normalized or Normalized and Tempered	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max.	A60LV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	A60LV
	Over 275	Quenched and Tempered	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max.	A60KV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	A60KV
19. PRECIPITATION HARDENING STAINLESS STEELS, CAST ASTM A351: Grade CD-4MCu ACI Grade CB-7Cu ACI Grade CD-4MCu 17-4 PH AM-355	325 to 450	Solution Treated or Solution Treated and Aged	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max	A60KV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	A60KV

See section 16 for Cutting Fluid Recommendations

*See section 8.12 for Work Traverse Rates. As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm.

†Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter work. For LARGER diameter work—use a softer grade and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Also see section 20.2, Grinding Guidelines.

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm	THRUFEED OF WORK* in/min	INFEED on dia. in/pass	WHEEL IDENTIFI-CATION† ANSI
			m/s	m/min	mm/pass	ISO
21. GRAY CAST IRONS **Ferritic** ASTM A48: Class 20 SAE J431c: Grade G1800 **Pearlitic- Ferritic** ASTM A48: Class 25 SAE J431c: Grade G2500 **Pearlitic** ASTM A48: Classes 30, 35, 40 SAE J431c: Grade G3000	45 R_C max.	As Cast, Annealed or Quenched and Tempered	5500 to 6500	50 to 150	Rough .005 Finish .002 max	C46LV or A60KV
			28 to 33	1.3 to 3.8	Rough .13 Finish .050 max.	C46LV or A60KV
Pearlitic + Free Carbides ASTM A48: Classes 45, 50 SAE J431c. Grades G3500, G4000 **Pearlitic or Acicular + Free Carbides** ASTM A48: Classes 55, 60	45 R_C to 52 R_C	As Cast, Annealed or Quenched and Tempered	5500 to 6500	50 to 150	Rough. .005 Finish .0015 max	C54KV or A60JV
			28 to 33	1.3 to 3.8	Rough .13 Finish .038 max.	C54KV or A60JV
	48 R_C to 60 R_C	Flame or Induction Hardened	5500 to 6500	50 to 150	Rough .004 Finish. .001 max	C60JV
			28 to 33	1.3 to 3.8	Rough .10 Finish .025 max.	C60JV
Austenitic (NI-RESIST) ASTM A436: Types 1, 1b, 2, 2b, 3, 4, 5, 6	100 to 250	As Cast	5500 to 6500	50 to 150	Rough: .005 Finish: 0015 max.	A60LV
			28 to 33	1.3 to 3.8	Rough .13 Finish .038 max.	A60LV
22. COMPACTED GRAPHITE CAST IRONS	185 to 255	As Cast	5500 to 6500	50 to 150	Rough: .005 Finish. .002 max.	C46LV
			28 to 33	1.3 to 3.8	Rough .13 Finish .050 max.	C46LV
			28 to 33	1.3 to 3.8	Rough .13 Finish .050 max.	C46LV or A60KV

See section 16 for Cutting Fluid Recommendations.

*See section 8.12 for Work Traverse Rates. As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm.

†Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter work. For LARGER diameter work—use a softer grade and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Also see section 20.2, Grinding Guidelines.

8.11 Centerless Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm / m/s	THRUFEED OF WORK* in/min / m/min	INFEED on dia in/pass / mm/pass	WHEEL IDENTIFI-CATION† ANSI / ISO
23. DUCTILE CAST IRONS **Ferritic** ASTM A536 Grades 60-40-18, 65-45-12 SAE J434c Grades D4018, D4512 **Ferritic- Pearlitic** ASTM A536 Grade 80-55-06 SAE J434c Grade D5506 **Pearlitic- Martensitic** ASTM A536 Grade 100-70-03 SAE J434c Grade D7003 **Martensitic** ASTM A536 Grade 120-90-02 SAE J434c Grade DQ&T	52 R_C max	Annealed, As Cast, Normalized and Tempered or Quenched and Tempered	5500 to 6500 28 to 33	50 to 150 1.3 to 3.8	Rough: .005 Finish .0015 max Rough: .13 Finish: .038 max.	C54KV C54KV
	53 R_C to 60 R_C	Flame or Induction Hardened	5500 to 6500 28 to 33	50 to 150 1.3 to 3.8	Rough .004 Finish: .001 max. Rough: .102 Finish: .025 max.	C60JV C60JV
Austenitic (NI-RESIST Ductile) ASTM A439 Types D-2, D-2B, D-2C, D-3, D-3A, D-4, D-5, D-5B ASTM A571 Type D-2M	120 to 275	Annealed	5500 to 6500 28 to 33	50 to 150 1.3 to 3.8	Rough .005 Finish .0015 max Rough: .13 Finish: .038 max.	A60LV A60LV
24. MALLEABLE CAST IRONS **Ferritic** ASTM A47 Grades 32510, 35018 ASTM A602 Grade M3210 SAE J158 Grade M3210 **Pearlitic** ASTM A220 Grades 40010, 45006, 45008, 50005 ASTM A602 Grade M4504, M5003 SAE J158 Grades M4504, M5003 **Tempered Martensite** ASTM A220 Grades 60004, 70003, 80002, 90001 ASTM A602 Grades M5503, M7002, M8501 SAE J158 Grades M5503, M7002, M8501	52 R_C max	Malleablized or Malleablized and Heat Treated	5500 to 6500 28 to 33	50 to 150 1.3 to 3.8	Rough .005 Finish .0015 max Rough: .13 Finish: .038 max.	C54KV C54KV
	Over 52 R_C	Flame or Induction Hardened	5500 to 6500 28 to 33	50 to 150 1.3 to 3.8	Rough .004 Finish .001 max. Rough: .102 Finish: .025 max.	C60JV C60JV
25. WHITE CAST IRONS (ABRASION RESISTANT) ASTM A532 Class I, Types A, B, C, D Class II, Types A, B, C, D, E Class III, Type A	60 R_C max	As Cast, Annealed or Hardened	5500 to 6500 28 to 33	50 to 150 1.3 to 3.8	Rough .004 Finish .001 max. Rough: .102 Finish: .025 max.	C60JV C60JV

See section 16 for Cutting Fluid Recommendations

*See section 8.12 for Work Traverse Rates. As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm.

†Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter work. For LARGER diameter work—use a softer grade and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Also see section 20.2, Grinding Guidelines.

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm / m/s	THRUFEED OF WORK* in/min / m/min	INFEED on dia. in/pass / mm/pass	WHEEL IDENTIFI-CATION† ANSI / ISO
26. HIGH SILICON CAST IRONS Duriron Duriclor ASTM A518	52 R_C	As Cast	5500 to 6500 28 to 33	50 to 150 1.3 to 3.8	Rough 004 Finish. 001 max Rough .102 Finish .025 max.	C60JV C60JV
27. CHROMIUM-NICKEL ALLOY CASTINGS ASTM A560 Grades 50Cr-50Ni, 60Cr-40Ni	275 to 375	As Cast	5500 to 6500 28 to 33	50 to 150 1.3 to 3.8	Rough 005 Finish 0015 max Rough .13 Finish .038 max.	C60KV C60KV
28. ALUMINUM ALLOYS, WROUGHT EC 2218 5252 6253 1060 2219 5254 6262 1100 2618 5454 6463 1145 3003 5456 6951 1175 3004 5457 7001 1235 3005 5652 7004 2011 4032 5657 7005 2014 5005 6053 7039 2017 5050 6061 7049 2018 5052 6063 7050 2021 5056 6066 7075 2024 5083 6070 7079 2025 5086 6101 7175 2117 5154 6151 7178	30 to 150 500kg	Cold Drawn or Solution Treated and Aged	5500 to 6500 28 to 33	50 to 150 1.3 to 3.8	Rough .005 Finish 0015 max Rough .13 Finish .038 max.	C54JV C54JV
29. ALUMINUM ALLOYS, CAST **Sand and Permanent Mold** A140 295 0 514 0 A712 0 201 0 B295 0 A514 0 D712 0 208 0 308 0 B514 0 713 0 213 0 319 0 520 0 771 0 222 0 355.0 535.0 850 0 224 0 C355 0 705.0 A850.0 242 0 B443 0 707 0 B850.0 Hiduminium RR-350 **Die Castings** C443 0 518 0	40 to 125 500kg	As Cast or Solution Treated and Aged	5500 to 6500 28 to 33	50 to 150 1.3 to 3.8	Rough 005 Finish .0015 max. Rough .13 Finish .038 max.	C54JV C54JV

See section 16 for Cutting Fluid Recommendations

*See section 8 12 for Work Traverse Rates As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm

†Wheel recommendations are for wet grinding 0 8- to 2-inch [20 to 50 mm] diameter work For LARGER diameter work—use a softer grade and/or coarser grit wheel For SMALLER diameter work—use a harder grade wheel. Also see section 20 2, Grinding Guidelines

8.11 Centerless Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm	THRUFEED OF WORK* in/min	INFEED on dia. in/pass	WHEEL IDENTIFI-CATION† ANSI
29. ALUMINUM ALLOYS, CAST (cont.) **Sand and Permanent Mold** 328.0 356.0 A332.0 A356.0 F332.0 357.0 333.0 359.0 354.0 **Die Castings** 360.0 A380.0 390.0 A413.0 A360.0 383.0 392.0 380.0 A384.0 413.0	40 to 125 500kg	As Cast or Solution Treated and Aged	5500 to 6500	50 to 150	Rough: .005 Finish .0015 max.	A60IV
30. MAGNESIUM ALLOYS, WROUGHT‡‡ AZ21A HK31A AZ31B HM21A AZ31C HM31A AZ61A ZK40A AZ80A ZK60A	50 to 90 500kg	Annealed, Cold Drawn or Solution Treated and Aged	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max	C60KV
31. MAGNESIUM ALLOYS, CAST‡‡ AM60A AZ91C ZE41A AM100A AZ92A ZE63A AS41A EZ33A ZH62A AZ63A HK31A ZK51A AZ81A HZ32A ZK61A AZ91A K1A AZ91B QE22A	50 to 90 500kg	As Cast, Annealed or Solution Treated and Aged	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max	C60KV
32. TITANIUM ALLOYS, WROUGHT‡‡ **Commercially Pure** 99.5 99.2 99.0 98.9 Ti-0.2Pd TiCODE-12	110 to 275	Annealed	4000 to 5500	50 to 150	Rough: .001 Finish: .0005 max.	C60KV‡

See section 16 for Cutting Fluid Recommendations

*See section 8.12 for Work Traverse Rates. As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm.

†Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter work. For LARGER diameter work—use a softer grade and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Also see section 20.2, Grinding Guidelines.

‡Use friable (green grit) silicon carbide.

‡‡CAUTION: Potential Fire Hazard. Exercise caution in grinding and disposing of swarf. Do NOT use water or water-miscible cutting fluids for magnesium alloys.

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm / m/s	THRUFEED OF WORK* in/min / m/min	INFEED on dia. in/pass / mm/pass	WHEEL IDENTIFI-CATION† ANSI / ISO
Alpha and Alpha-Beta Alloys Ti-8Mn Ti-1Al-8V-5Fe Ti-2Al-11Sn-5Zr-1Mo Ti-3Al-2.5V Ti-5Al-2Sn-2Zr-4Mo-4Cr (Ti-17) Ti-5Al-2.5Sn Ti-5Al-2.5Sn ELI Ti-5Al-6Sn-2Zr-1Mo Ti-6Al-2Cb-1Ta-0.8Mo Ti-6Al-4V Ti-6Al-4V ELI Ti-6Al-6V-2Sn Ti-6Al-2Sn-4Zr-2Mo Ti-6Al-2Sn-4Zr-2Mo-.25Si Ti-6Al-2Sn-4Zr-6Mo Ti-7Al-4Mo Ti-8Al-1Mo-1V	300 to 380	Annealed	4000 to 5500	50 to 150	Rough: .001 Finish: .0005 max	C60KV‡
			20 to 28	1.3 to 3.8	Rough: .025 Finish: .013 max	C60KV‡
	320 to 440	Solution Treated and Aged	4000 to 5500	50 to 150	Rough: .001 Finish: .0005 max	C60KV‡
			20 to 28	1.3 to 3.8	Rough: .025 Finish: .013 max	C60KV‡
Beta Alloys Ti-3Al-8V-6Cr-4Mo-4Zr Ti-8Mo-8V-2Fe-3Al Ti-11.5Mo-6Zr-4.5Sn Ti-10V-2Fe-3Al Ti-13V-11Cr-3Al	275 to 350	Annealed or Solution Treated	4000 to 5500	50 to 150	Rough: .001 Finish: .0005 max.	C60KV‡
			20 to 28	1.3 to 3.8	Rough: .025 Finish: .013 max.	C60KV‡
	350 to 440	Solution Treated and Aged	4000 to 5500	50 to 50	Rough: .001 Finish: .0005 max.	C60KV‡
			20 to 28	1.3 to 3.8	Rough: .025 Finish: .013 max.	C60KV‡
33. TITANIUM ALLOYS, CAST‡‡ **Commercially Pure** 99.0 Ti-0.2Pd ASTM B367, Grades C-1, C-2, C-3, C-4, C-7A, C-7B, C-8A, C-8B	150 to 250	As Cast or As Cast and Annealed	4000 to 5500	50 to 150	Rough: .001 Finish: .0005 max.	C60KV‡
			20 to 28	1.3 to 3.8	Rough: .025 Finish: .013 max.	C60KV‡
Alpha and Alpha-Beta Alloys Ti-5Al-2.5Sn Ti-6Al-4V Ti-6Al-2Sn-4Zr-2Mo Ti-8Al-1Mo-1V ASTM 367: Grades C-5, C-6	300 to 350	As Cast or As Cast and Annealed	4000 to 5500	50 to 150	Rough: .001 Finish: .0005 max.	C60KV‡
			20 to 28	1.3 to 3.8	Rough: .025 Finish: .013 max.	C60KV‡

See section 16 for Cutting Fluid Recommendations

*See section 8.12 for Work Traverse Rates. As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm.

†Wheel recommendations are for wet grinding 0.8- to 2-inch (20 to 50 mm) diameter work. For LARGER diameter work—use a softer grade and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Also see section 20.2, Grinding Guidelines.

‡Use friable (green grit) silicon carbide

‡‡CAUTION: Potential Fire Hazard. Exercise caution in grinding and disposing of swarf.

8.11 Centerless Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	THRUFEED OF WORK* in/min m/min	INFEED on dia. in/pass mm/pass	WHEEL IDENTIFI-CATION† ANSI ISO
34. COPPER ALLOYS, WROUGHT 101 116 143 182 102 119 145 184 104 120 147 185 105 121 150 187 107 122 155 189 109 125 162 190 110 127 165 191 111 128 170†† 192 113 129 172†† 194 114 130 173†† 195 115 142 175††	10 R_B to 70 R_B	Annealed	5500 to 6500 28 to 33	50 to 150 1.3 to 3.8	Rough: 005 Finish: 0015 max Rough: .13 Finish: .038 max.	C54KV C54KV
	60 R_B to 100 R_B	Cold Drawn	5500 to 6500 28 to 33	50 to 150 1.3 to 3.8	Rough 005 Finish 0015 max Rough: .13 Finish: .038 max.	C54KV C54KV
210 332 368 464 220 335 370 465 226 340 377 466 230 342 385 467 240 349 411 482 260 350 413 485 268 353 425 667 270 356 435 687 280 360 442 688 314 365 443 694 316 366 444 330 367 445	10 R_B to 70 R_B	Annealed	5500 to 6500 28 to 33	50 to 150 1.3 to 3.8	Rough 005 Finish. 0015 max. Rough: .13 Finish: .038 max.	C54KV C54KV
	60 R_B to 100 R_B	Cold Drawn	5500 to 6500 28 to 33	50 to 150 1.3 to 3.8	Rough 005 Finish: .0015 max. Rough: .13 Finish: .038 max.	C54KV C54KV
505 613 632 510 614 638 511 618 642 521 619 651 524 623 655 544 624 674 608 625 675 610 630	10 R_B to 70 R_B	Annealed	5500 to 6500 28 to 33	50 to 150 1.3 to 3.8	Rough: 005 Finish: .0015 max Rough: .13 Finish: .038 max.	C54KV C54KV
	60 R_B to 100 R_B	Cold Drawn	5500 to 6500 28 to 33	50 to 150 1.3 to 3.8	Rough: .005 Finish: .0015 max. Rough: .13 Finish: .038 max.	C54KV C54KV

See section 16 for Cutting Fluid Recommendations

*See section 8.12 for Work Traverse Rates. As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm

†Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter work. For LARGER diameter work—use a softer grade and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Also see section 20.2, Grinding Guidelines

††CAUTION: Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm / m/s	THRUFEED OF WORK* in/min / m/min	INFEED on dia. in/pass / mm/pass	WHEEL IDENTIFI-CATION† ANSI / ISO
706 752 710 754 715 757 725 770 745 782	10 R_B to 70 R_B	Annealed	5500 to 6500	50 to 150	Rough: 005 Finish 0015 max	C54KV
			28 to 33	1.3 to 3.8	Rough: 13 Finish: .038 max.	C54KV
	60 R_B to 100 R_B	Cold Drawn	5500 to 6500	50 to 150	Rough 005 Finish: 0015 max	C54KV
			28 to 33	1.3 to 3.8	Rough: 13 Finish: .038 max.	C54KV
35. COPPER ALLOYS, CAST						
801 814 824††	40 to 200 500kg	As Cast or Heat Treated	5500 to 6500	50 to 150	Rough 005 Finish. .0015 max	C54KV
803 815 825††						
805 817†† 826††						
807 818†† [illegible]††						
809 820†† 828††						
811 821††						
813 822††			28 to 33	1.3 to 3.8	Rough: 13 Finish: .038 max.	C54KV
	34 R_C to 45 R_C	Heat Treated	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max.	A60LV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	A60LV
833 854 867 834 855 868 836 857 872 838 858 874 842 861 875 844 862 876 848 863 878 852 864 879 853 865	35 to 200 500kg	As Cast	5500 to 6500	50 to 150	Rough. .005 Finish: .0015 max	C54KV
			28 to 33	1.3 to 3.8	Rough: 13 Finish: .038 max.	C54KV
902 916 934 948 903 917 935 952 905 922 937 953 907 923 938 954 909 925 939 955 910 926 943 956 911 927 944 957 913 928 945 958 915 932 947	40 to 100 500kg	As Cast	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max.	C54KV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	C54KV

See section 16 for Cutting Fluid Recommendations

*See section 8.12 for Work Traverse Rates. As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm

†Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter work. For LARGER diameter work—use a softer grade and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Also see section 20.2, Grinding Guidelines

††CAUTION: Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions.

8.11 Centerless Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	THRUFEED OF WORK* in/min m/min	INFEED on dia. in/pass mm/pass	WHEEL IDENTIFI-CATION† ANSI ISO
35. COPPER ALLOYS, CAST (cont.) (materials listed on preceding page)	Over 100 500kg	As Cast or Heat Treated	5500 to 6500	50 to 150	Rough .005 Finish .0015 max	A60LV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	A60LV
962 963 964 966†† 973 974 976 978 993	50 to 100 500kg	As Cast	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max	C54KV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	C54KV
	Over 100 500kg	As Cast or Heat Treated	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max.	A60LV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	A60LV
36. NICKEL ALLOYS, WROUGHT AND CAST Nickel 200 Nickel 201 Nickel 205 Nickel 211 Nickel 220 Nickel 230	80 to 170	Annealed or Cold Drawn	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max.	C60KV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	C60KV
MONEL Alloy 400 MONEL Alloy 401 MONEL Alloy 404 MONEL Alloy R405 ASTM A296 Grades CZ-100, M-35 ASTM A494: Grades CZ-100, M-35	115 to 240	Annealed, Cold Drawn or Cast	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max.	C60KV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	C60KV
DURANICKEL Alloy 301 MONEL Alloy 502 MONEL Alloy K500 NI-SPAN-C Alloy 902 PERMANICKEL Alloy 300	150 to 320	Solution Treated	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max.	C60KV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	C60KV

See section 16 for Cutting Fluid Recommendations

*See section 8.12 for Work Traverse Rates. As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm

†Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter work. For LARGER diameter work—use a softer grade and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Also see section 20.2, Grinding Guidelines

††CAUTION: Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	THRUFEED OF WORK* in/min m/min	INFEED on dia. in/pass mm/pass	WHEEL IDENTIFI-CATION† ANSI ISO
36. NICKEL ALLOYS, WROUGHT AND CAST (cont.) (materials listed on preceding page)	330 to 360	Aged	5500 to 6500	50 to 150	Rough .003 Finish .001 max	C60KV
			28 to 33	1.3 to 3.8	Rough: .075 Finish: .025 max.	C60KV
37. BERYLLIUM NICKEL ALLOYS, WROUGHT AND CAST†† Berylco 440 Berylco 41C Berylco 42C Berylco 43C Brush Alloy 200C Brush Alloy 220C Brush Alloy 260C	200 to 250	As Cast or Solution Treated	5500 to 6500	50 to 150	Rough: 005 Finish 0015 max.	A60LV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	A60LV
	283 to 425	Hardened or Aged	5500 to 6500	50 to 150	Rough: .003 Finish .001 max.	A60KV
			28 to 33	1.3 to 3.8	Rough: .075 Finish: .025 max.	A60KV
	47 R_C to 52 R_C	Hardened or Aged	5500 to 6500	50 to 150	Rough: 002 Finish: .001 max	A60JV
			28 to 33	1.3 to 3.8	Rough: .050 Finish: .025 max.	A60JV
38. NITINOL ALLOYS, WROUGHT Nitinol 55Ni-45Ti Nitinol 56Ni-44Ti Nitinol 60Ni-40Ti	210 to 340	Wrought or Annealed	4000 to 6000	50 to 150	Rough: 003 Finish: .001 max.	C60KV or CA60PB
			20 to 30	1.3 to 3.8	Rough: .075 Finish: .025 max.	C60KV or CA60PB
	48 R_C to 52 R_C	Quenched	4000 to 6000	50 to 150	Rough: .001 Finish: .0005 max.	C60JV or CA60PB
			20 to 30	1.3 to 3.8	Rough: .025 Finish: .013 max.	C60JV or CA60PB

See section 16 for Cutting Fluid Recommendations

*See section 8.12 for Work Traverse Rates As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm

†Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter work For LARGER diameter work—use a softer grade and/or coarser grit wheel For SMALLER diameter work—use a harder grade wheel. Also see section 20.2, Grinding Guidelines

††CAUTION Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions

8.11 Centerless Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	THRUFEED OF WORK* in/min m/min	INFEED on dia. in/pass mm/pass	WHEEL IDENTIFI-CATION† ANSI ISO
39. HIGH TEMPERATURE ALLOYS, WROUGHT AND CAST						
Nickel Base, Wrought						
AF2-1DA	200 to 390	Annealed or Solution Treated	3000 to 4000	50 to 150	Rough: .003 Finish .001 max	A60KV
			15 to 20	1.3 to 3.8	Rough: .075 Finish: .025 max	A60KV
Astroloy						
Haynes Alloy 263						
IN-102						
Incoloy Alloy 901						
Incoloy Alloy 903						
Inconel Alloy 617						
Inconel Alloy 625						
Inconel Alloy 700	300 to 475	Solution Treated and Aged	3000 to 4000	50 to 150	Rough: .003 Finish .001 max	A60KV
			15 to 20	1.3 to 3.8	Rough: .075 Finish: .025 max	A60KV
Inconel Alloy 702						
Inconel Alloy 706						
Inconel Alloy 718						
Inconel Alloy 721						
Inconel Alloy 722						
Inconel Alloy X-750						
Inconel Alloy 751						
M252						
Nimonic 75						
Nimonic 80						
Nimonic 90						
Nimonic 95						
Rene 41						
Rene 63						
Rene 77						
Rene 95						
Udimet 500						
Udimet 700						
Udimet 710						
Unitemp 1753						
Waspaloy						
Nickel Base, Wrought						
Hastelloy Alloy B	140 to 220	Annealed or Solution Treated	3000 to 4000	50 to 150	Rough: .003 Finish: .001 max.	A60KV
			15 to 20	1.3 to 3.8	Rough: .075 Finish: .025 max	A60KV
Hastelloy Alloy B-2						
Hastelloy Alloy C						
Hastelloy Alloy C-276						
Hastelloy Alloy G						
Hastelloy Alloy S						
Hastelloy Alloy X						
Incoloy Alloy 804						
Incoloy Alloy 825						
Inconel Alloy 600	240 to 310	Cold Drawn or Aged	3000 to 4000	50 to 150	Rough: 003 Finish: .001 max.	A60KV
			15 to 20	1.3 to 3.8	Rough: .075 Finish: .025 max	A60KV
Inconel Alloy 601						
Refractaloy 26						
Udimet 630						

See section 16 for Cutting Fluid Recommendations

*See section 8.12 for Work Traverse Rates. As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm

†Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter work. For LARGER diameter work—use a softer grade and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Also see section 20.2, Grinding Guidelines.

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	THRUFEED OF WORK* in/min m/min	INFEED on dia. in/pass mm/pass	WHEEL IDENTIFI-CATION† ANSI ISO
Nickel Base, Wrought TD-Nickel†† TD-Ni-Cr††	180 to 200	As Rolled	5500 to 6500 28 to 33	50 to 150 1.3 to 3.8	Rough: .005 Finish: .0015 max. Rough: .13 Finish: .038 max.	A60KV A60KV
Nickel Base, Cast B-1900 GMR-235 GMR-235D Hastelloy Alloy B Hastelloy Alloy C Hastelloy Alloy D IN-100 (Rene 100) IN-738 IN-792 Inconel Alloy 713C Inconel Alloy 718 M252 MAR-M200 MAR-M246 MAR-M421 MAR-M432 Rene 80 Rene 125 SEL SEL 15 TRW VI A Udimet 500 Udimet 700 ASTM A296: Grades CW-12M, N-12M, CY-40 ASTM A297: Grades HW, HX ASTM A494: Grades N-12M-1, N-12M-2, CY-40, CW-12M-1, CW-12M-2 ASTM A608: Grades HW50, HX50	200 to 425	As Cast or Cast and Aged	3000 to 4000 15 to 20	50 to 150 1.3 to 3.8	Rough: .003 Finish .001 max. Rough: .07[illegible] Finish: .025 max.	A60KV A60KV
Cobalt Base, Wrought AiResist 213 Haynes Alloy 25 (L605) Haynes Alloy 188 J-1570 MAR-M905 MAR-M918 S-816 V 36	180 to 230	Solution Treated	3000 to 4000 15 to 20	50 to 150 1.3 to 3.8	Rough: .003 Finish: .001 max. Rough: .075 Finish: .025 max.	A60KV A60KV
	270 to 320	Solution Treated and Aged	3000 to 4000 15 to 20	50 to 150 1.3 to 3.8	Rough: .003 Finish: .001 max Rough: .075 Finish: .025 max.	A60KV A60KV

See section 16 for Cutting Fluid Recommendations

*See section 8.12 for Work Traverse Rates. As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 30 rpm

†Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter work. For LARGER diameter work—use a softer grade and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Also see section 20.2, Grinding Guidelines.

††CAUTION: Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions

8.11 Centerless Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	THRUFEED OF WORK* in/min m/min	INFEED on dia. in/pass mm/pass	WHEEL IDENTIFI-CATION† ANSI ISO
39. HIGH TEMPERATURE ALLOYS, WROUGHT AND CAST (cont.)						
Cobalt Base, Cast						
AiResist 13 AiResist 215 FSX-414 HS-6 HS-21 HS-31 (X-40) HOWMET #3 MAR-M302 MAR-M322 MAR-M509 NASA Co-W-Re WI-52 X-45	220 to 290	As Cast or Cast and Aged	3000 to 4000	50 to 150	Rough: 003 Finish .001 max.	A60KV
			15 to 20	1.3 to 3.8	Rough: .075 Finish: .025 max.	A60KV
	290 to 425	As Cast or Cast and Aged	3000 to 4000	50 to 150	Rough: .003 Finish: .001 max	A60KV
			15 to 20	1.3 to 3.8	Rough: .075 Finish: .025 max.	A60KV
Iron Base, Wrou[illegible]						
A-286 Discaloy Incoloy Alloy 800 Incoloy Alloy 800H Incoloy Alloy 801 Incoloy Alloy 802 N-155 V-57 W-545 16-25-6 19-9DL	180 to 230	Solution Treated	3000 to 4000	50 to 150	Rough: .003 Finish: .001 max.	A60KV
			15 to 20	1.3 to 3.8	Rough: .075 Finish: .025 max.	A60KV
	250 to 320	Solution Treated and Aged	3000 to 4000	50 to 150	Rough: .003 Finish: .001 max.	A60KV
			15 to 20	1.3 to 3.8	Rough: .075 Finish: .025 max.	A60KV
40. REFRACTORY ALLOYS, WROUGHT, CAST, P/M**						
Columbium †† ‡‡**						
C103 C129Y Cb-1Zr Cb-752 FS-85 FS-291 WC-3015	170 to 225	Stress Relieved	4000	50 to 150	Rough: .001 Finish: .0005 max.	A60LV
			20	1.3 to 3.8	Rough: .025 Finish: .013 max.	A60LV

See section 16 for Cutting Fluid Recommendations

*See section 8.12 for Work Traverse Rates As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm

†Wheel recommendations are for wet grinding 0 8- to 2-inch [20 to 50 mm] diameter work For LARGER diameter work—use a softer grade and/or coarser grit wheel For SMALLER diameter work—use a harder grade wheel Also see section 20 2, Grinding Guidelines.

**Due to the brittleness of refractory alloys, cracking, chipping, flaking and breakout tend to occur, particularly on the edges of the machined surfaces

††CAUTION· Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions

‡‡CAUTION· Potential Fire Hazard. Exercise caution in grinding and disposing of swarf

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	THRUFEED OF WORK* in/min m/min	INFEED on dia. in/pass mm/pass	WHEEL IDENTIFI-CATION† ANSI ISO
Molybdenum** Mo Mo-50Re TZC TZM	220 to 290	Stress Relieved	2000 to 4000	50 to 150	Rough: .001 Finish: .0005 max	A60MV
			10 to 20	1.3 to 3.8	Rough: .025 Finish: .013 max.	A60MV
Tantalum** ASTAR 811C T-111 T-222 Ta-10W Ta-Hf Ta63	200 to 250	Stress Relieved	2000 to 4000	50 to 150	Rough .001 Finish .0005 max.	A60KV
			10 to 20	1.3 to 3.8	Rough: .025 Finish: .013 max.	A60KV
Tungsten** 85% density 93% density 96% density 100% density	190 to 320	Pressed and Sintered, Forged, or Arc Cast	2000	50 to 150	Rough: .001 Finish: .0003 max	C70LV
			10	1.3 to 3.8	Rough: .025 Finish: .008 max.	C70LV
Tungsten - 2 Thoria** ††	260 to 320	Pressed and Sintered	2000	50 to 150	Rough: .001 Finish 0005 max.	C70LV
			10	1.3 to 3.8	Rough: .025 Finish: .013 max.	C70LV
Tungsten Alloys** GE-218 W-15Mo W-5Re W-25Re W-25Re-30Mo	260 to 320	As Cast	2000	50 to 150	Rough: .001 Finish: .0005 max.	C70LV
			10	1.3 to 3.8	Rough: .025 Finish: .013 max.	C70LV
Tungsten Alloys** Gyromet Mallory 2000 W-10Ag W-7Ni-4Cu	290 to 320	Pressed and Sintered	2000	50 to 150	Rough: 001 Finish. .0005 max.	C70LV
			10	1.3 to 3.8	Rough: .025 Finish: .013 max.	C70LV

See section 16 for Cutting Fluid Recommendations

*See section 8.12 for Work Traverse Rates As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm.

†Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter work For LARGER diameter work—use a softer grade and/or coarser grit wheel For SMALLER diameter work—use a harder grade wheel Also see section 20 2, Grinding Guidelines

**Due to the brittleness of refractory alloys, cracking, chipping, flaking and breakout tend to occur, particularly on the edges of the machined surfaces

††CAUTION Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions.

8.11 Centerless Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm / m/s	THRUFEED OF WORK* in/min / m/min	INFEED on dia. in/pass / mm/pass	WHEEL IDENTIFI-CATION† ANSI / ISO
40. REFRACTORY ALLOYS, WROUGHT, CAST, P/M (cont.)**						
Tungsten Alloys**						
Anviloy 1100	290 to 320	Pressed and Sintered	2000	50 to 150	Rough .001 Finish .0005 max	C70L V
Anviloy 1150						
Anviloy 1200						
			10	1.3 to 3.8	Rough: .025 Finish: .013 max.	C70LV
44. URANIUM, WROUGHT†† ‡‡	56 R_A to 58 R_A	Annealed	4000 to 6000	75 to 125	Rough .005 Finish .002 max	C46JB or C46KV
			20 to 30	1.9 to 3.2	Rough: .13 Finish: .050 max.	C46JB or C46KV
45. ZIRCONIUM ALLOYS, WROUGHT‡‡						
Zr-2%Hf (Grade 11)	140 to 280	Rolled, Extruded or Forged	3000	50 to 150	Rough .001 Finish .0005 max	Rough: A60TB or CA60RB Finish: CA80PB
Zr-0.001%Hf (Grade 21)						
Zircaloy 2 (Grade 32)						
Zircaloy 4 (Grade 34)						
			15	1.3 to 3.8	Rough: .025 Finish: .013 max.	Rough: A60TB or CA60RB Finish: CA80PB
47. POWDER METAL ALLOY §§						
Copper§§	50 R_F to 70 R_F	As Sintered	5500 to 6500	50 to 150	Rough .005 Finish: .0015 max.	C54KV
			26 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	C54KV
Brasses§§	35 R_H to 81 R_H	As Sintered	5500 to 6500	50 to 150	Rough: .005 Finish .0015 max	C54KV
CZP-0218-T						
CZP-0218-U						
CZP-0218-W						
90Cu-10Zn						
90Cu-10Zn-0.5Pb						
70Cu-30Zn						
68.5Cu-30Zn-1.5Pb			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	C54KV
Bronzes§§	30 R_F to 75 R_F	As Sintered	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max.	C54KV
CT-0010-N						
CT-0010-R						
CT-0010-S						
95Cu-5Al						
77Cu-15Pb-7Sn-1Fe-1C						
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	C54KV

See section 16 for Cutting Fluid Recommendations

*See section 8.12 for Work Traverse Rates. As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm

†Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter work. For LARGER diameter work—use a softer grade and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Also see section 20.2, Grinding Guidelines

**Due to the brittleness of refractory alloys, cracking, chipping, flaking and breakout tend to occur, particularly on the edges of the machined surfaces

††CAUTION: Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions

‡‡CAUTION: Potential Fire Hazard. Exercise caution in grinding and disposing of swarf

§§Grinding of low-density parts is not recommended because surface porosity will be reduced or lost

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm / m/s	THRUFEED OF WORK* in/min / m/min	INFEED on dia. in/pass / mm/pass	WHEEL IDENTIFI-CATION† ANSI / ISO
Copper-Nickel Alloys§§ CZN-1818-T CZN-1818-U CZN-1818-W CZNP-1618-U CZNP-1618-W 90Cu-10Ni 62Cu-18Ni-18Zn-2Sn	22 R_H to 100 R_H	As Sintered	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max.	C54KV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	C54KV
Nickel§§	45 R_B	As Sintered	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max.	A46KV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	A46KV
Nickel Alloys§§ 67Ni-30Cu-3Fe	34 R_B to 50 R_B	As Sintered	5500 to 6500	50 to 150	Rough: .005 Finish: .0015 max.	C60JV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	C60JV
Refractory Metal Base§§ 87W-13Cu 85W-15Ag 74W-26Cu 72.5W-27.5Ag 65W-35Ag 56W+C-44Cu 55W-45Cu 51W-49Ag 50W+C-50Ag	101 to 260	As Sintered	2000	50 to 150	Rough: .001 Finish: .0005 max.	C70LV
			5 to 10	1.3 to 3.8	Rough: .025 Finish: .013 max.	C70LV
Refractory Metal Base§§ 61Mo-39Ag 50Mo-50Ag	75 R_B to 82 R_B	As Sintered	2000 to 4000	50 to 150	Rough: .001 Finish: .0005 max.	A60MV
			10 to 20	1.3 to 3.8	Rough: .025 Finish: .013 max.	A60MV

See section 16 for Cutting Fluid Recommendations

*See section 8.12 for Work Traverse Rates. As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm.

†Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter work. For LARGER diameter work—use a softer grade and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Also see section 20.2, Grinding Guidelines.

§§Grinding of low-density parts is not recommended because surface porosity will be reduced or lost.

8.11 Centerless Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	THRUFEED OF WORK* in/min m/min	INFEED on dia. in/pass mm/pass	WHEEL IDENTIFI-CATION† ANSI ISO
47. POWDER METAL ALLOYS§§ (cont.)						
Irons§§						
F-0000-N F-0000-P F-0000-R F-0000-S F-0000-T	50 to 67 500kg	As Sintered	5500 to 6500	50 to 150	Rough: .005 Finish: .002 max.	C46LV or A60KV
			28 to 33	1.3 to 3.8	Rough: 13 Finish: .050 max.	C46LV or A60KV
Steels§§						
F-0008-P F-0008-S F-0005-S FC-0205-S FC-0208-P FC-0208-S FC-0508-P FC-1000-N FN-0205-S	101 to 426	As Sintered or Heat Treated	5500 to 6500	50 to 150	Rough: 005 Finish 0015 max	A60NV
			28 to 33	1.3 to 3.8	Rough: 13 Finish: .038 max.	A60NV
FN-0205-T FN-0405-R FN-0405-S FN-0405-T FX-1005-T FX-2008-T						
Stainless Steels§§						
SS-303-R SS-304-R SS-316-R SS-410-R	107 to 285	As Sintered or Heat Treated	5500 to 6500	50 to 150	Rough: 005 Finish* .0015 max.	C60LV
			28 to 33	1.3 to 3.8	Rough: 13 Finish: .038 max.	C60LV
Aluminum Alloys§§						
90 5Al-5Sn-4Cu 88Al-5Sn-4Pb-3Cu Al-1Mg-0.6Si-0 25Cu Al-0.6Mg-0.4Si Al-4.4Cu-0 8Si-0.4Mg	55 R_H to 98 R_H	Solution Treated and Aged	5500 to 6500	50 to 150	Rough: 005 Finish* .0015 max	C54JV
			28 to 33	1.3 to 3.8	Rough: 13 Finish: .038 max.	C54JV
49. CARBIDES						
Titanium Carbide Tungsten Carbide	89 R_A to 94 R_A	—	5500 to 6500	50 to 60	Rough: 001 Finish: .0003 max.	C60KV
			28 to 33	1.3 to 1.5	Rough: 025 Finish: .008 max.	C60KV

See section 16 for Cutting Fluid Recommendations.

*See section 8 12 for Work Traverse Rates As recommended starting conditions– use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm

†Wheel recommendations are for wet grinding 0 8- to 2-inch [20 to 50 mm] diameter work For LARGER diameter work—use a softer grade and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel Also see section 20.2, Grinding Guidelines

§§Grinding of low-density parts is not recommended because surface porosity will be reduced or lost

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	THRUFEED OF WORK* in/min m/min	INFEED on dia. in/pass mm/pass	WHEEL IDENTIFI-CATION† ANSI ISO
50. FREE MACHINING MAGNETIC ALLOYS Magnetic Core Iron-FM (up to 2 5% Si)	185 to 240	Wrought	5500 to 6500	50 to 150	Rough 005 Finish. 0015 max	A60LV
			28 to 33	1.3 to 3.8	Rough .13 Finish .038 max.	A60LV
Hi Perm 49-FM	185 to 240	Wrought	5500 to 6500	50 to 150	Rough: .005 Finish .0015 max	C60LV
			28 to 33	1.3 to 3.8	Rough .13 Finish .038 max.	C60LV
51. MAGNETIC ALLOYS Magnetic Core Iron (up to 4% Si)	185 to 240	Wrought	5500 to 6500	50 to 150	Rough 005 Finish. 0015 max	A60MV
			28 to 33	1.3 to 3.8	Rough .13 Finish .038 max.	A60MV
Hi Perm 49 HyMu 80	185 to 240	Wrought	5500 to 6500	50 to 150	Rough. 005 Finish· .0015 max	C60LV
			28 to 33	1.3 to 3.8	Rough .13 Finish .038 max.	C60LV
Alnico I Alnico II Alnico III Alnico IV Alnico V Alnico V-7 Alnico XII Columax-5 Hyflux Alnico V-7	45 R_C to 58 R_C	As Cast	5500 to 6500	50 to 150	Rough: .003 Finish· .001 max.	A60KV
			28 to 33	1.3 to 3.8	Rough .08 Finish .025 max.	A60KV
52. FREE MACHINING CONTROLLED EXPANSION ALLOYS Invar 36	125 to 220	Annealed or Cold Drawn	5500 to 6500	50 to 150	Rough: .005 Finish· .0015 max.	C60LV
			28 to 33	1.3 to 3.8	Rough .13 Finish .038 max.	C60LV

See section 16 for Cutting Fluid Recommendations.

*See section 8 12 for Work Traverse Rates As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm

†Wheel recommendations are for wet grinding 0 8- to 2-inch [20 to 50 mm] diameter work For LARGER diameter work—use a softer grade and/or coarser grit wheel For SMALLER diameter work—use a harder grade wheel Also see section 20 2, Grinding Guidelines

8.11 Centerless Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm	THRUFEED OF WORK* in/min	INFEED on dia. in/pass	WHEEL IDENTIFI-CATION† ANSI
			m/s	m/min	mm/pass	ISO
53. CONTROLLED EXPANSION ALLOYS Invar Kovar	125 to 250	Annealed or Cold Drawn	5500 to 6500	50 to 150	Rough 005 Finish: 0015 max	C60LV
			28 to 33	1.3 to 3.8	Rough: .13 Finish: .038 max.	C60LV
54. CARBONS & GRAPHITES Mechanical Grades	40 to 100 Shore	Molded or Extruded	5000 to 6500	50	Rough .005 Finish .001 max	C36NV
			25 to 33	1.3	Rough: .13 Finish: .025 max.	C36NV
Brush Grade Carbon	8 to 90 Shore	Molded or Extruded	5000 to 6500	50	Rough: .005 Finish 001 max	C36NV
			25 to 33	1.3	Rough: .13 Finish: .025 max.	C36NV
Graphite	—	—	5000 to 6500	50	Rough 005 Finish: 001 max	Rough: C36JV Finish, C60JV
			25 to 33	1.3	Rough: .13 Finish: .025 max.	Rough: C36JV Finish: C60JV
55. GLASSES & CERAMICS Glass	480 to 530 Knoop 100g	—	5500 to 6500	50 to 150	Rough: 002 Finish. .001 max.	C100LV
			28 to 33	1.3 to 3.8	Rough: .050 Finish: .025 max.	C100LV
Porcelain Enamel	—	—	5500 to 6500	50 to 150	Rough: 002 Finish. .001 max.	C60LV
			28 to 33	1.3 to 3.8	Rough: .050 Finish: .025 max.	C60LV

See section 16 for Cutting Fluid Recommendations

*See section 8.12 for Work Traverse Rates. As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm

†Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter work. For LARGER diameter work—use a softer grade and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Also see section 20.2, Grinding Guidelines

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm m/s	THRUFEED OF WORK* in/min m/min	INFEED on dia. in/pass mm/pass	WHEEL IDENTIFI-CATION† ANSI ISO
Ceramics Alumina (Aluminum Oxide) Alumina-Mullite Aluminum Silicate Beryllia (Beryllium Oxide)†† Magnesia (Magnesium Oxide) Mullite Silicon Carbide Silicon Nitride Thoria (Thorium Oxide)†† Titania (Titanium Oxide) Titanium Diboride†† Zircon (Zirconium Silicate) Zirconia (Zirconium Oxide)	Over 800 Knoop	Fired	5500 to 6500 28 to 33	50 to 150 1.3 to 3.8	Rough: 001 Finish: .0002 max. Rough: 025 Finish: .005 max.	Rough: C46KV Finish: C80KV Rough: C46KV Finish: C80KV
56. PLASTICS **Thermoplastics**	—	Cast, Molded, Extruded, or Filled and Molded	5000 to 6000 25 to 30	5 to 30 13 to 76	Rough: 005- 020 Finish: .003 max. Rough: .12-.38 Finish: .075 max.	C60KV C60KV
Thermosetting Plastics	—	Cast	5500 to 6500 28 to 33	5 to 30 13 to 76	Rough: .005-.020 Finish .003 max. Rough: .13-.50 Finish: .075 max.	C46KV C46KV
	—	Molded	5500 to 6500 28 to 33	5 to 30 13 to 76	Rough: .005-.020 Finish: .003 max Rough: .13-.50 Finish: .075 max.	C46MV C46MV
	—	Laminated	5500 to 6500 28 to 33	5 to 30 13 to 76	Rough: .005-.020 Finish: .003 max. Rough: .13-.50 Finish: .075 max.	C36NV C36

See section 16 for Cutting Fluid Recommendations

*See section 8.12 for Work Traverse Rates. As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm

†Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter work. For LARGER diameter work—use a softer grade and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Also see section 20.2, Grinding Guidelines

††CAUTION. Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions

8.11 Centerless Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm	THRUFEED OF WORK* in/min	INFEED on dia. in/pass	WHEEL IDENTIFI-CATION† ANSI
58. FLAME (THERMAL) SPRAYED MATERIALS						
Sprayed Carbides						
Chromium Carbide			5500 to 6500	20 to 90	Rough: .001 Finish. .0005 max	C80HV
Chromium Carbide-Cobalt Blend	—	—				
Columbium Carbide						
Tantalum Carbide						
Titanium Carbide						
Tungsten Carbide						
Tungsten Carbide-Cobalt						
Tungsten Carbide (Cobalt)-Nickel Alloy Blend						
Inorganic Coating Materials						
Alumina (Pure)			5500 to 6500	20 to 90	Rough: .001 Finish. .0005 max.	C80IV
Alumina (Grey) containing Titania						
Alumina, Nickel-Aluminide Blends						
Barium Titanate	—	—				
Boron††						
Calcium Titanate						
Calcium Zirconate						
Chromium Disilicide††						
Chromium Oxide††						
Cobalt (40%), Zirconia Blend						
Columbium (Niobium)††						
Glass (Kovar sealing)††						
Hexaboron Silicide††						
Magnesia Alumina Spinel						
Magnesium Zirconate						
Molybdenum Disilicide						
Mullite						
Nickel (40%), Alumina Blend						
Nickel Oxide						
Rare Earth Oxides						
Tantalum						
Titania (50%), Alumina Blend						
Titanium Oxide						
Tungsten						
Yttrium Zirconate						
Zirconia (Lime Stabilized)						
Zirconia, Nickel-Aluminide Blends						
Zirconium Oxide (Hafnia Free, Lime Stabilized)						
Zirconium Silicate						
Sprayed Metals (Group I)						
Co-Cr-B Alloy (Self Fluxing)			5500 to 6500	20 to 90	Rough: .001 Finish: .0005 max.	C60JV
Ni-Cr-B Alloy (Self Fluxing)						
Nickel Chrome Steel (Special)						
Stainless Steel	—	—				

See section 16 for Cutting Fluid Recommendations

*See section 8.12 for Work Traverse Rates. As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm

†Wheel recommendations are for wet grinding 0.8- to 2-inch [20 to 50 mm] diameter work. For LARGER diameter work—use a softer grade and/or coarser grit wheel. For SMALLER diameter work—use a harder grade wheel. Also see section 20.2, Grinding Guidelines

††CAUTION: Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions

MATERIAL	HARD-NESS Bhn	CONDITION	WHEEL SPEED fpm	THRUFEED OF WORK* in/min	INFEED on dia. in/pass	WHEEL IDENTIFI-CATION† ANSI
Sprayed Metals (Group II) Bronze Chromium Cobalt Nickel Molybdenum Monel	—	—	5500 to 6500	20 to 90	Rough 001 Finish. .0005 max	C60KV
Sprayed Metals (Group III) Carbon Steel Iron Precipitation Hardening Steel	—	—	5500 to 6500	20 to 90	Rough· .001 Finish· 0005 max.	C60LV
59. PLATED MATERIALS Chromium Plate	—	—	3000 to 4000	50 to 150	Rough. 002 Finish· .0005 max.	A150JV
Nickel Plate Silver Plate	—	—	5500 to 6500	50 to 150	Rough: .003 Finish· .001 max	A60KV
61. RUBBER	Hard	—	5500 to 6500	50 to 150	Rough: .005 Finish· .0015 max.	C30KV

See section 16 for Cutting Fluid Recommendations

*See section 8 12 for Work Traverse Rates As recommended starting conditions—use a regulating wheel angle with a positive inclination of 3° and a regulating wheel speed of 25 to 40 rpm

†Wheel recommendations are for wet grinding 0 8- to 2-inch [20 to 50 mm] diameter work For LARGER diameter work—use a softer grade and/or coarser grit wheel For SMALLER diameter work—use a harder grade wheel Also see section 20 2, Grinding Guidelines

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Centerless Grinding—Work Traverse Rates 8.12

REG. WHEEL ANGLE	REG. WHEEL DIA. inches*	APPROXIMATE THRUFEED WORK TRAVERSE RATES inches per minute* Regulating Wheel Speeds										
		10 rpm	15 rpm	20 rpm	25 rpm	30 rpm	40 rpm	50 rpm	70 rpm	90 rpm	125 rpm	160 rpm
1°	8 0	4.4	6.6	8.8	11.0	13.2	17.5	21.9	30.7	39.5	54 8	70 2
	8 5	4.7	7.0	9.3	11.6	14 0	18 6	23 3	32.6	41 9	58.2	74.6
	9.0	4 9	7.4	9 9	12 3	14 8	19.7	24.7	34.5	44.4	61 7	78.9
	9 5	5 2	7 8	10.4	13.0	15.6	20.8	26 0	36 5	46.9	65.1	83.3
	10.0	5.5	8 2	11.0	13.7	16.4	21 9	27 4	38.4	49.3	68.5	87.7
	10.5	5.8	8.6	11 5	14.4	17.3	23 0	28.8	40.3	51.8	72.0	92.1
	11.0	6 0	9 0	12.1	15.1	18.1	24.1	30.2	42 2	54.3	75.4	96 5
	11.5	6.3	9 5	12 6	15.8	18 9	25 2	31.5	44.1	56.7	78 8	100.9
	12.0	6 6	9 9	13.2	16 4	19.7	26 3	32.9	46.0	59.2	82.2	105 3
	12 5	6.9	10.3	13.7	17.1	20.5	27 4	34.2	47.9	61.6	85.6	109 7
	13.0	7.1	10.7	14.3	17.8	21 3	28.5	35.6	49.8	64.1	89 0	114.1
	13.5	7.4	11.1	14.8	18 5	22.1	29.6	36.9	51.7	66.5	92 4	118.5
	14.0	7 6	11.5	15 4	19.2	22.9	30.7	38.3	53.6	69.0	95.8	122.9
2°	8 0	8.8	13.2	17.5	21.9	26 3	35.1	43.9	61.4	78.9	109.6	140.3
	8.5	9.3	14.0	18.6	23 3	28.0	37.3	46.6	65 2	83.9	116.5	149.1
	9.0	9 9	14.8	19.7	24.7	29.6	39.5	49 3	69.1	88.8	123 3	157.9
	9.5	10.4	15.6	20.8	26.0	31.2	41.7	52.1	72.9	93 7	130.2	166.7
	10.0	11.0	16 4	21.9	27.4	32.9	43 9	54.8	76.7	98.7	137.1	175 4
	10.5	11.5	17.3	23 0	28 8	34.5	46 0	57.6	80 6	103 6	143.9	184.2
	11 0	12.1	18 1	24.1	30 2	36.2	48.2	60 3	84.4	108.5	150.8	193.0
	11 5	12.6	18 9	25.2	31.5	37.8	50.4	63.0	88 3	113 5	157.6	201 7
	12.0	13.2	19.7	26.3	32.9	39 5	52.6	65.8	92.1	118.4	164.5	210.5
	12.5	13.7	20.5	27.4	33 2	41.1	54 8	68.5	96.0	123.4	171 3	219.2
	13 0	14.3	21.3	28.5	33.6	42.8	57.0	71.3	99.8	128.3	174.2	228.5
	13.5	14.8	22.1	29.6	33.9	44.4	59.2	74.0	103.7	133.3	177.0	236.7
	14.0	15.4	22.9	30.7	34.3	46.1	61.4	76.8	107.5	138.2	183.9	245.5
3°	8.0	13.2	19.7	26.3	32 9	39.5	52.6	65 8	92.1	118.4	164.4	210.5
	8.5	14.0	21.0	28.0	34.9	41.9	55.9	69.9	97.8	125.8	174.7	223.6
	9.0	14.8	22.2	29.6	37.0	44.4	59 2	74.0	103.6	133.2	185.0	236.8
	9.5	15 6	23.4	31.2	39.1	46.9	62.5	78.1	109.3	140.6	195.3	249.9
	10.0	16.4	24.7	32.9	41.1	49 3	65.8	82.2	115.1	148.0	205.5	263.1
	10.5	17.3	25.9	34.5	43.2	51 8	69.1	86 3	120.9	155.4	215 8	276.2
	11 0	18.1	27.1	36 2	45.2	54.3	72.3	90 4	126 6	162.8	226.1	289.4
	11.5	18.9	28.4	37.8	47.3	56 7	75.6	94 5	132.4	170.2	236.4	302.6
	12 0	19.7	29.6	39.5	49.3	59.2	78.9	98 7	138.1	177.6	246 6	315.7
	12 5	20.5	30 9	41.1	51.4	61.6	82.2	102 8	143.9	185.0	256.9	328 8
	13.0	21.3	32.1	42.8	53.4	64.1	85 5	106.9	149.6	192 4	267.2	341.9
	13.5	22.1	33.4	44.4	55.5	66 5	88.8	111 0	155.4	199.8	277.5	355.0
	14.0	22 9	34.6	46.1	57.5	69.0	92.1	115.1	161.1	207.2	287.8	368.1
4°	8.0	17 5	26.3	35.1	43 8	52 6	70.1	87.7	122.7	157.8	219.2	280.5
	8.5	18.6	27.9	37.3	46.6	55 9	74.5	93.1	130.4	167.7	232.9	298.1
	9.0	19.7	29.6	39.4	49 3	59.2	78 9	98.6	138.1	177.5	246.6	315.6
	9.5	20 8	31.2	41.6	52.1	62.5	83.3	104.1	145.7	187.4	260.3	333.1
	10.0	21.9	32.9	43.8	54.8	65.7	87.7	109.6	153.4	197.2	273.9	350.7
	10.5	23.0	34.5	46.0	57.5	69.0	92 0	115.1	161.1	207.1	287.6	368.2
	11.0	24.1	36.2	48.2	60 3	72 3	96 4	120.5	168.8	217.0	301.3	385.7
	11.5	25 2	37.8	50.4	63.0	75.6	100.8	126 0	176.4	226.8	315.0	403.3
	12.0	26.3	39 4	52.6	65.7	78.9	105 2	131.5	184.1	236.7	328.7	420.8
	12.5	27.4	41.0	54.8	68.5	82.2	109 6	136.9	191.7	246.5	342.4	438.4
	13 0	28.5	42 6	57.0	71.3	85.5	114.0	142.4	199.4	256.4	356 1	456.0
	13 5	29.6	44.2	59 2	74.1	88.8	118.4	147.8	207.0	266.2	369.8	473.6
	14.0	30.7	45.8	61.4	76 9	92.1	122.8	153.3	214.7	276.1	383.5	491.2

*To convert inches per minute to millimeters per minute multiply by 25 4

'To convert inches to millimeters multiply by 25.4.

8.12 Centerless Grinding--Work Traverse Rates

REG. WHEEL ANGLE	REG WHEEL DIA.	APPROXIMATE THRUFEED WORK TRAVERSE RATES inches per minute*										
		Regulating Wheel Speeds										
	inches†	10 rpm	15 rpm	20 rpm	25 rpm	30 rpm	40 rpm	50 rpm	70 rpm	90 rpm	125 rpm	160 rpm
5°	8 0	21 9	32.9	43.8	54.8	65 7	87.6	109.5	153.3	197 2	273 8	350 5
	8 5	23 3	34 9	46 5	58 2	69 8	93.1	116.4	162.9	209.5	290 9	372 4
	9 0	24 6	37.0	49.3	61 6	73 9	98.6	123 2	172.5	221 8	308.0	394.3
	9.5	26.0	39 0	52.0	65.0	78 0	104.1	130 1	182.1	234.1	325 2	416.2
	10 0	27 4	41.1	54.8	68.5	82.1	109.5	136.9	191.7	246.4	342.3	438.1
	10 5	28 8	43.1	57 5	71 9	86.3	115.0	143.8	201.3	258 8	359 4	460 0
	11 0	30 1	45.2	60.2	75 3	90.4	120.5	150.6	210 8	271.1	376.5	481.9
	11 5	31 5	47 2	63 0	78.7	94 5	126.0	157 4	220.4	283.4	393.6	503.8
	12 0	32.9	49.3	65 7	82 1	98 6	131.4	164.3	230.0	295.7	410 7	525 7
	12.5	34 3	51.3	68 5	85 5	102 7	136.9	171.2	239 6	308.0	427 8	547.6
	13.0	35 7	53.4	71 2	88 9	106.8	142.4	178 1	249 2	320.3	444.9	569 5
	13.5	37 1	55 4	74 0	92.3	110.9	147.9	185.0	258.8	332 6	462 0	591.4
	14 0	38.5	57.5	76.7	95.7	115.0	153.4	191.9	268.4	344.9	479.1	613.3
6°	8.0	26.3	39 4	52.5	65 7	78.8	105.1	131 4	183 9	236.4	328.4	420 3
	8.5	27.9	41.9	55 8	69.8	83.7	111.7	139.6	195.4	251.2	348.9	446 6
	9 0	29 6	44 3	59 1	73 9	88.7	118.2	147.8	206.9	266 0	369.4	472 9
	9.5	31 2	46.8	62 4	78.0	93.6	124.8	156.0	218.4	280.8	390.0	499.2
	10 0	32.8	49 3	65.7	82.1	98.5	131.4	164 2	229.9	295.6	410 5	525.4
	10 5	34.5	51.7	69.0	86.2	103.4	137.9	172.4	241.4	310.3	431 0	551 7
	11 0	36.1	54.2	72.2	90.3	108.4	144.5	180.6	252.9	325 1	451 5	578 0
	11.5	37.8	56.6	75.5	94.4	113.3	151.1	188.8	264.4	339.9	472 1	604.2
	12.0	39.4	59.1	78.8	98.5	118.2	157.6	197.0	275.8	354.7	492.6	630.5
	12.5	41 0	61 6	82.1	102.6	123.1	164.3	205.2	287 4	369.5	513 1	656.8
	13.0	42 6	64.1	85.4	106.7	128.0	170.9	213.4	298.9	384.3	533.6	683.1
	13.5	44.2	66.6	88.7	110.8	132.9	177.5	221.6	310.4	399.1	554.1	709.4
	14 0	45 8	69.1	92.0	114.9	137.8	184.1	229.8	321.9	413.9	574.6	735.7
7°	8.0	30.6	45.9	61.3	76.6	91.9	122.5	153 1	214.4	275.7	382.9	490.1
	8.5	32 5	48.8	65.1	81.4	97.6	130 2	162.7	227.8	292.9	406.8	520.7
	9 0	34.5	51.7	68.9	86.1	103.4	137.8	172.3	241 2	310.1	430 7	551.3
	9 5	36.4	54.6	72.7	90.9	109.1	145.5	181.9	254.6	327.4	454.7	582.0
	10.0	38 3	57.4	76.6	95.7	114 9	153.1	191.4	268.0	344.6	478.6	612.6
	10.5	40 2	60 3	80.4	100.5	120 6	160.8	201 0	281.4	361.8	502.5	643.2
	11.0	42 1	63 2	84.2	105.3	126 3	168.5	210.6	294.8	379.0	526.4	673.8
	11.5	44.0	66 0	88.1	110.1	132.1	176.1	220.1	308.2	396.3	550 4	704.5
	12 0	15 9	68.9	91.9	114.9	137.8	183.8	229.7	321.6	413.5	574.3	735.1
	12 5	47.8	71.8	95.7	119.7	143.5	191.5	239.3	335.0	430.7	598.2	765.7
	13.0	49.7	74.7	99.5	124.5	149.2	199.2	248.9	348.4	447.9	622.1	796.3
	13.5	51.6	77.6	103.3	129 3	154.9	206.9	258.5	361.8	465.1	646 0	826.9
	14.0	53.5	80.5	107.1	134.1	160.6	214.6	268.1	375.2	482.3	669.9	857.5
8°	8.0	35.0	52.5	70.0	87 4	104.9	139.9	174.9	244 8	314 8	437.2	559.6
	8.5	37.2	55.7	74 3	92.9	111.5	148.7	185.8	260 1	334 5	464.5	594.6
	9 0	39.3	59.0	78.7	98.4	118.0	157.4	196.7	275.4	354.1	491.9	629.6
	9.5	41.5	62.3	83.1	103.8	124.6	166.1	207.7	290.7	373.8	519.2	664.6
	10 0	43 7	65.6	87 4	109 3	131.2	174.9	218.6	306.1	393.5	546.5	699.5
	10.5	45.9	68.9	91.8	114.8	137.7	183.6	229.5	321.4	413.2	573.8	734.5
	11.0	48.1	72.1	96.2	120.2	144.3	192.4	240.5	336 7	432.8	601.2	769.5
	11.5	50.3	75.4	100 6	125.7	150.8	201.1	251.4	352.0	452 5	628.5	804.5
	12.0	52.5	78.7	104.9	131.2	157.4	209.9	262.3	367 3	472.2	655.8	839 5
	12 5	54.7	82 0	109 3	136.7	164.0	218.6	273.2	382 6	491.9	683.1	874.5
	13 0	56 9	85.3	113 6	142.2	170.6	227.4	284.1	397.9	511.6	710.4	909.5
	13 5	59.1	88.6	118.0	147.7	177.2	236.1	295.0	413.2	531 3	737.7	944 5
	14.0	61.3	91.9	122.3	153.2	183 8	244.9	305.9	428.5	551.0	765 0	979.5

*To convert inches per minute to millimeters per minute multiply by 25.4
†To convert inches to millimeters multiply by 25 4.

MATERIAL	HARDNESS Bhn	CONDITION	OPERATION	ABRASIVE TYPE	GRAIN SIZE	BELT SPEED* fpm m/s	CONTACT WHEEL TYPE†	CONTACT WHEEL HARDNESS Durometer IRHD‡
CARBON STEELS, ALLOY STEELS, AND TOOL STEELS; WROUGHT AND CAST	100 to 45 R_C	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	Roughing	Al_2O_3, Al_2O_3-ZrO_2	24-60	4000-5500	SR	70-95
			Polishing	Al_2O_3	80-320	4500-6500	SR, SFR	20-60
			Roughing	Al_2O_3, Al_2O_3-ZrO_2	24-60	20-28	SR	70-95
			Polishing	Al_2O_3	80-320	23-33	SR, SFR	20-60
	45 R_C to 56 R_C	Quenched and Tempered	Roughing	Al_2O_3, Al_2O_3-ZrO_2	40-80	2500-4500	SR	70-95
			Polishing	Al_2O_3	100-320	3000-4500	SR, SFR	20-60
			Roughing	Al_2O_3, Al_2O_3-ZrO_2	40-80	13-23	SR	70-95
			Polishing	Al_2O_3	100-320	15-23	SR, SFR	20-60
STAINLESS STEELS, WROUGHT AND CAST	135 to 56 R_C	Annealed, Cold Drawn or Quenched and Tempered	Roughing	Al_2O_3, Al_2O_3-ZrO_2	36-60	2000-4000	SR	70-95
			Polishing	Al_2O_3	80-320	3000-5500	SR, SFR	20-60
			Roughing	Al_2O_3, Al_2O_3-ZrO_2	36-80	10-20	SR	70-95
			Polishing	Al_2O_3	80-320	15-28	SR, SFR	20-60
GRAY CAST IRONS DUCTILE CAST IRONS MALLEABLE CAST IRONS	100 to 400	All	Roughing	Al_2O_3, Al_2O_3-ZrO_2	24-60	3000-4500 6000-9000	SR, SFR	70-95
			Polishing	Al_2O_3	80-180	4000-5500	SR, SFR	20-60
			Roughing	Al_2O_3, Al_2O_3-ZrO_2	24-60	15-23 30-46	SR, SFR	70-95
			Polishing	Al_2O_3	80-180	20-28	SR, SFR	20-60
ALUMINUM ALLOYS, WROUGHT AND CAST MAGNESIUM ALLOYS;‡‡ WROUGHT AND CAST	30 to 150 500kg	Cold Drawn, As Cast or Solution Treated and Aged	Roughing	Al_2O_3, SiC	24-80	5000-6500	SR, SFR	70-95
			Polishing	Al_2O_3, SiC	100-240	5000-6000	SR, SFR, B	20-60
			Roughing	Al_2O_3, SiC	24-80	25-33	SR, SFR	70-95
			Polishing	Al_2O_3, SiC	100-240	25-40	SR, SFR, B	20-60
TITANIUM ALLOYS,‡‡ WROUGHT AND CAST	110 to 440	Annealed Solution Treated or Solution Treated and Aged	Roughing	SiC, Al_2O_3, Al_2O_3-ZrO_2	50-80	1000-2500	SR	70-95
			Polishing	SiC	100-240	1200-2500	SR, SFR	20-60
			Roughing	SiC, Al_2O_3, Al_2O_3-ZrO_2	50-80	5-13	SR	70-95
			Polishing	SiC	100-240	5-13	SR, SFR	20-60

See section 16 for Cutting Fluid Recommendations

*Use lower values of BELT SPEED when good surface integrity is required.

†SR—Serrated Rubber, SFR—Smooth Face Rubber, B—Buff Type Serrations are usually at 45° angle, although some heavy stock removal operations use 60°. Widths of lands and grooves vary from narrow lands and wide grooves for fast aggressive cuts to wide lands and narrow grooves for intermediate and finishing operations depending upon workpiece shape and operating conditions

‡IRHD (International Rubber Hardness degrees) is approximately equal to the durometer reading

‡‡CAUTION Potential Fire Hazard Exercise caution in grinding and disposing of swarf Do NOT use water or water-miscible cutting fluids for magnesium alloys

8.13 Abrasive Belt Grinding

MATERIAL	HARDNESS Bhn	CONDITION	OPERATION	ABRASIVE TYPE	GRAIN SIZE	BELT SPEED* fpm / m/s	CONTACT WHEEL TYPE†	CONTACT WHEEL HARDNESS Durometer IRHD‡
COPPER ALLOYS,** WROUGHT AND CAST	10 R_B to 100 R_B	Annealed or Cold Drawn	Roughing	Al_2O_3, SiC	24-80	2000-4500	SR, SFR	70-95
			Polishing	Al_2O_3, SiC	100-240	4000-6000	SR, SFR, B	20-60
			Roughing	Al_2O_3, SiC	24-80	10-23	SR, SFR	70-95
			Polishing	Al_2O_3, SiC	100-240	20-30	SR, SFR, B	20-60
HIGH TEMPERATURE ALLOYS, WROUGHT AND CAST Nickel, Cobalt and Iron Base	140 to 475	All	Roughing	Al_2O_3, Al_2O_3-ZrO_2	40-80	2000-4500	SR	70-95
			Polishing	Al_2O_3	100-240	3000-5500	SR, SFR	20-60
			Roughing	Al_2O_3, Al_2O_3-ZrO_2	40-80	10-23	SR	70-95
			Polishing	Al_2O_3	100-240	15-20	SR, SFR	20-60
ZINC ALLOYS, CAST	80 to 100	As Cast	Roughing	Al_2O_3, SiC	150-220	5000-10,000	SR, B	40-95
			Polishing	Al_2O_3, SiC	220-320	5000-10,000	SR, B	20-60
			Roughing	Al_2O_3, SiC	150-220	25-40	SR, B	40-95
			Polishing	Al_2O_3, SiC	220-320	25-50	SR, B	20-60

See section 16 for Cutting Fluid Recommendations

*Use lower values of BELT SPEED when good surface integrity is required

†SR—Serrated Rubber, SFR—Smooth Face Rubber, B—Buff Type Serrations are usually at 45° angle, although some heavy stock removal operations use 60° Widths of lands and grooves vary from narrow lands and wide grooves for fast aggressive cuts to wide lands and narrow grooves for intermediate and finishing operations, depending upon workpiece shape and operating conditions

‡IRHD (International Rubber Hardness degrees) is approximately equal to the durometer reading

**CAUTION Beryllium-copper alloys are Toxic Materials, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions . . . See section 8.11 for specific beryllium-copper alloys indicated by **

MATERIAL	HARD-NESS Bhn	CONDITION	THREADS PER INCH / PITCH (P) mm	WHEEL IDENTIFI-CATION ANSI / ISO	WHEEL SPEED fpm / m/s	WORK SPEED fpm / m/min
1. FREE MACHINING CARBON STEELS, WROUGHT **Low Carbon Resulfurized** 1108 1116 1211 1109 1117 1212 1110 1118 1213 1115 1119 1215 **Medium Carbon Resulfurized** 1132 1140 1145 1137 1141 1146 1139 1144 1151 **Low Carbon Leaded** 10L18 12L13 12L15 11L17 12L14 **Medium Carbon Leaded** 10L45 11L37 11L44 10L50 11L41	50 R_C max	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	4 to 12 13 to 27 28 to 63 64 to 80 6 to 2.5 2 to 1 .8 to .45 .4 to .35	A90RB A120SB A180TB A220UB A90RB A120SB A180TB A220UB	8500 9000 9500 10000 43 46 48 51	4.0 1.2
	Over 50 R_C	Carburized and/or Quenched and Tempered	4 to 12 13 to 27 28 to 63 64 to 80 6 to 2.5 2 to 1 .8 to .45 .4 to .35	A100KV A150JV A220MV A240PV A100KV A150JV A220MV A240PV	7000 7500 8500 9000 36 38 43 46	6.0 1.8
2. CARBON STEELS - WROUGHT **Low Carbon** 1005 1012 1019 1026 1006 1013 1020 1029 1008 1015 1021 1513 1009 1016 1022 1518 1010 1017 1023 1522 1011 1018 1025 **Medium Carbon** 1030 1042 1053 1541 1033 1043 1055 1547 1035 1044 1524 1548 1037 1045 1525 1551 1038 1046 1526 1552 1039 1049 1527 1040 1050 1536 **High Carbon** 1060 1074 1085 1566 1064 1075 1086 1572 1065 1078 1090 1069 1080 1095 1070 1084 1561	50 R_C max.	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	4 to 12 13 to 27 28 to 63 64 to 80 6 to 2.5 2 to 1 .8 to .45 .4 to .35	A90RB A120SB A180TB A220UB A90RB A120SB A180TB A220UB	8500 9000 9500 10000 43 46 48 51	4.0 1.2
	Over 50 R_C	Carburized and/or Quenched and Tempered	4 to 12 13 to 27 28 to 63 64 to 80 6 to 2.5 2 to 1 .8 to .45 .4 to .35	A100KV A150JV A220MV A240PV A100KV A150JV A220MV A240PV	7000 7500 8500 9000 36 38 43 46	6.0 1.8
3. CARBON AND FERRITIC ALLOY STEELS (HIGH TEMPERATURE SERVICE) ASTM A369 Grades FPA, FPB, FP1, FP2, FP3b, FP5, FP7, FP9, FP11, FP12, FP21, FP22	150 to 200	As Forged, Annealed or Normalized and Tempered	4 to 12 13 to 27 28 to 63 64 to 80 6 to 2.5 2 to 1 .8 to .45 .4 to .35	A90RB A120SB A180TB A220UB A90RB A120SB A180TB A220UB	8500 9000 9500 10000 43 46 48 51	4.0 1.2

See section 16 for Cutting Fluid Recommendations
See section 20 for additional information

8.14 Thread Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	THREADS PER INCH / PITCH (P) mm	WHEEL IDENTIFICATION ANSI / ISO	WHEEL SPEED fpm / m/sec	WORK SPEED fpm / m/min
4. FREE MACHINING ALLOY STEELS, WROUGHT **Medium Carbon Resulfurized** 4140 4145Se 4140Se 4147Te 4142Te 4150 **Medium and High Carbon Leaded** 41L30 41L47 51L32 86L40 41L40 41L50 52L100 41L45 43L40 86L20	50 R_C max	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	4 to 12 13 to 27 28 to 63 64 to 80	A90RB A120SB A180TB A220UB	8500 9000 9500 10000	4.0
			6 to 2.5 2 to 1 0.8 to .45 0.4 to .35	A90RB A120SB A180TB A220UB	43 46 48 51	1.2
	Over 50 R_C	Carburized and/or Quenched and Tempered	4 to 12 13 to 27 28 to 63 64 to 80	A100KV A150JV A220MV A240PV	7000 7500 8500 9000	6.0
			6 to 2.5 2 to 1 0.8 to .45 0.4 to .35	A100KV A150JV A220MV A240PV	36 38 43 46	1.8
5. ALLOY STEELS, WROUGHT **Low Carbon** 4012 4615 4817 8617 4023 4617 4820 8620 4024 4620 5015 8622 4118 4621 5115 8822 4320 4718 5120 9310 4419 4720 6118 94B15 4422 4815 8115 94B17 **Medium Carbon** 1330 4145 5132 8640 1335 4147 5135 8642 1340 4150 5140 8645 1345 4161 5145 86B45 4027 4340 5147 8650 4028 4427 5150 8655 4032 4626 5155 8660 4037 50B40 5160 8740 4042 50B44 51B60 8742 4047 5046 6150 9254 4130 50B46 81B45 9255 4135 50B50 8625 9260 4137 5060 8627 94B30 4140 50B60 8630 4142 5130 8637 **High Carbon** 50100 51100 52100 M-50	50 R_C max	Hot Rolled, Normalized, Annealed, Cold Drawn or Quenched and Tempered	4 to 12 13 to 27 28 to 63 64 to 80	A90RB A120SB A180TB A220UB	8500 9000 9500 10000	4.0
			6 to 2.5 2 to 1 0.8 to .45 0.4 to .35	A90RB A120SB A180TB A220UB	43 46 48 51	1.2
	Over 50 R_C	Carburized and/or Quenched and Tempered	4 to 12 13 to 27 28 to 63 64 to 80	A100KV A150JV A220MV A240PV	7000 7500 8500 9000	6.0
			6 to 2.5 2 to 1 0.8 to .45 0.4 to .35	A100KV A150JV A220MV A240PV	36 38 43 46	1.8

See section 16 for Cutting Fluid Recommendations
See section 20 for additional information

MATERIAL	HARD-NESS Bhn	CONDITION	THREADS PER INCH / PITCH (P) mm	WHEEL IDENTIFI-CATION ANSI / ISO	WHEEL SPEED fpm / m/s	WORK SPEED fpm / m/min
6. HIGH STRENGTH STEELS, WROUGHT 300M 4330V 4340 4340Si 98BV40 D6ac H11 H13 HP 9-4-20 HP 9-4-25 HP 9-4-30 HP 9-4-45	50 R_C max	Annealed, Normalized or Quenched and Tempered	4 to 12 13 to 27 28 to 63 64 to 80 6 to 2.5 2 to 1 .8 to .45 .4 to .35	A90RB A120SB A180TB A220UB A90RB A120SB A180TB A220UB	8500 9000 9500 10000 43 46 48 51	4 0 1.2
	Over 50 R_C	Quenched and Tempered	4 to 12 13 to 27 28 to 63 64 to 80 6 to 2.5 2 to 1 .8 to .45 .4 to .35	A100KV A150JV A220MV A240PV A100KV A150JV A220MV A240PV	7000 7500 8500 9000 36 38 43 46	6 0 1.8
7. MARAGING STEELS, WROUGHT ASTM A538: Grades A, B, C 120 Grade 180 Grade 200 Grade 250 Grade 300 Grade 350 Grade HY230	50 R_C max	Annealed or Maraged	4 to 12 13 to 27 28 to 63 64 to 80 6 to 2.5 2 to 1 .8 to .45 .4 to .35	A90RB A120SB A180TB A220UB A90RB A120SB A180TB A220UB	8500 9000 9500 10000 43 46 48 51	4 0 1.2
	Over 50 R_C	Maraged	4 to 12 13 to 27 28 to 63 64 to 80 6 to 2.5 2 to 1 .8 to .45 .4 to .35	A100KV A150JV A220MV A240PV A100KV A150JV A220MV A240PV	7000 7500 8500 9000 36 38 43 46	6 0 1.8
8. TOOL STEELS, WROUGHT **Group I** A2 H13 L6 P20 A3 H14 L7 P21 A4 H19 O1 S1 A6 H21 O2 S2 A8 H22 O6 A9 H23 O7 A10 H24 P2 H10 H25 P4 H11 H26 P5 W2 H12 L2 P6 W5 SAE J438b. Types W108, W109, W110, W112, W209, W210, W310	50 R_C max	Annealed or Quenched and Tempered	4 to 12 13 to 27 28 to 63 64 to 80 6 to 2.5 2 to 1 .8 to .45 .4 to .35	A90RB A120SB A180TB A220UB A90RB A120SB A180TB A220UB	8500 9000 9500 10000 43 46 48 51	4 0 1.2
	Over 50 R_C	Quenched and Tempered	4 to 12 13 to 27 28 to 63 64 to 80 6 to 2.5 2 to 1 .8 to .45 .4 to .35	A100KV A150JV A220MV A240PV A100KV A150JV A220MV A240PV	7000 7500 8500 9000 36 38 43 46	6.0 1.8
Group II D2 H42 M42 D3 M1 T1 D4 M2 T2 D5 M3-1 T4 F1 M10 T8 F2 M30	50 R_C max	Annealed or Quenched and Tempered	4 to 12 13 to 27 28 to 63 64 to 80 6 to 2.5 2 to 1 .8 to .45 .4 to .35	A90RB A120SB A180TB A220UB A90RB A120SB A180TB A220UB	8500 9000 9500 10000 43 46 48 51	4 0 1.2

See section 16 for Cutting Fluid Recommendations
See section 20 for additional information

8.14 Thread Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	THREADS PER INCH / PITCH (P) mm	WHEEL IDENTIFI-CATION ANSI / ISO	WHEEL SPEED fpm / m/s	WORK SPEED fpm / m/min
8. TOOL STEELS, WROUGHT (cont.) **Group II (cont.)** (materials listed on preceding page)	50 R_C to 58 R_C	Quenched and Tempered	4 to 12	A100KV	7000	6 0
			13 to 27	A150JV	7500	
			28 to 63	A220MV	8500	
			64 to 80	A240PV	9000	
			6 to 2.5	A100KV	36	1.8
			2 to 1	A150JV	38	
			.8 to .45	A220MV	43	
			.4 to .35	A240PV	46	
	Over 58 R_C	Quenched and Tempered	4 to 12	A100KV	7000	6 0
			13 to 27	A150JV	7500	
			28 to 63	A240MV	8500	
			64 to 80	A280PV	9000	
			6 to 2.5	A100KV	36	1.8
			2 to 1	A150JV	38	
			.8 to .45	A240MV	43	
			.4 to .35	A280PV	46	
Group III A7 M33 M44 D7 M34 M46 M3-2 M36 M47 M6 M41 T5 M7 M43 T6	50 R_C max	Annealed or Quenched and Tempered	4 to 12	A90RB	8500	4 0
			13 to 27	A120SB	9000	
			28 to 63	A180TB	9500	
			64 to 80	A220UB	10000	
			6 to 2.5	A90RB	43	1.2
			2 to 1	A120SB	46	
			.8 to .45	A180TB	48	
			.4 to .35	A220UB	51	
	50 R_C to 58 R_C	Quenched and Tempered	4 to 12	A100KV	7000	4.0
			13 to 27	A150JV	7500	4 0
			28 to 63	A220MV	8500	6 0
			64 to 80	A240PV	9000	6 0
			6 to 2.5	A100KV	36	1.2
			2 to 1	A150JV	38	1.2
			.8 to .45	A220MV	43	1.8
			.4 to .35	A240PV	46	1.8
	Over 58 R_C	Quenched and Tempered	4 to 12	A100KV	7000	4 0
			13 to 27	A150JV	7500	4 0
			28 to 63	A240MV	8500	6.0
			64 to 80	A280PV	9000	6 0
			6 to 2.5	A100KV	36	1.2
			2 to 1	A150JV	38	1.2
			.8 to .45	A240MV	43	1.8
			.4 to .35	A280PV	46	1.8
Group IV M4 T15	50 R_C max	Annealed or Quenched and Tempered	4 to 12	A90RB	8500	4.0
			13 to 27	A120SB	9000	
			28 to 63	A180TB	9500	
			64 to 80	A220UB	10000	
			6 to 2.5	A90RB	43	1.2
			2 to 1	A120SB	46	
			.8 to .45	A180TB	48	
			.4 to .35	A220UB	51	
	50 R_C to 58 R_C	Quenched and Tempered	4 to 12	A100KV	7000	4 0
			13 to 27	A150JV	7500	4 0
			28 to 63	A220MV	8500	6 0
			64 to 80	A240PV	9000	6 0
			6 to 2.5	A100KV	36	1.2
			2 to 1	A150JV	38	1.2
			.8 to .45	A220MV	43	1.8
			.4 to .35	A240PV	46	1.8

See section 16 for Cutting Fluid Recommendations
See section 20 for additional information

MATERIAL	HARD-NESS Bhn	CONDITION	THREADS PER INCH / PITCH (P) mm	WHEEL IDENTIFI-CATION ANSI / ISO	WHEEL SPEED fpm / m/s	WORK SPEED fpm / m/min
8. TOOL STEELS, WROUGHT (cont.) **Group IV (cont.)** (materials listed on preceding page)	Over 58 R_C	Quenched and Tempered	4 to 12	A100KV	7000	4 0
			13 to 27	A150JV	7500	4 0
			28 to 63	A240MV	8500	6 0
			64 to 80	A280PV	9000	6 0
			6 to 2.5	A100KV	36	1.2
			2 to 1	A150JV	38	1.2
			.8 to .45	A240MV	43	1.8
			.4 to .35	A280PV	46	1.8
9. NITRIDING STEELS, WROUGHT Nitralloy 125, Nitralloy 135, Nitralloy 135 Mod, Nitralloy 225, Nitralloy 230, Nitralloy EZ, Nitralloy N, Nitrex 1	200 to 350	Annealed, Normalized or Quenched and Tempered	4 to 12	A90RB	8500	4 0
			13 to 27	A120SB	9000	
			28 to 63	A180TB	9500	
			64 to 80	A220UB	10000	
			6 to 2.5	A90RB	43	
			2 to 1	A120SB	46	
			.8 to .45	A180TB	48	1.2
			.4 to .35	A220UB	51	
	60 R_C to 65 R_C	Nitrided	4 to 12	A100JV	7000	6 0
			13 to 27	A150KV	7500	
			28 to 63	A220MV	8500	
			64 to 80	A240PV	9000	
			6 to 2.5	A100JV	36	1.8
			2 to 1	A150KV	38	
			.8 to .45	A220MV	43	
			.4 to .35	A240PV	46	
12. FREE MACHINING STAINLESS STEELS, WROUGHT **Ferritic** 430F, 430F Se	135 to 185	Annealed	4 to 12	A90RB	8500	4 0
			13 to 27	A120SB	9000	
			28 to 63	A180TB	9500	
			64 to 80	A220UB	10000	
			6 to 2.5	A90RB	43	1.2
			2 to 1	A120SB	46	
			.8 to .45	A180TB	48	
			.4 to .35	A220UB	51	
Austenitic 203EZ, 303, 303MA, 303Pb, 303 Plus X, 303Se	135 to 275	Annealed or Cold Drawn	4 to 12	A90RB	8500	4 0
			13 to 27	A120SB	9000	
			28 to 63	A180TB	9500	
			64 to 80	A220UB	10000	
			6 to 2.5	A90RB	43	1.2
			2 to 1	A120SB	46	
			.8 to .45	A180TB	48	
			.4 to .35	A220UB	51	
Martensitic 416, 416 Plus X, 416Se, 420F, 420F Se, 440F, 440F Se	135 to 240	Annealed or Cold Drawn	4 to 12	A90RB	8500	4 0
			13 to 27	A120SB	9000	
			28 to 63	A180TB	9500	
			64 to 80	A220UB	10000	
			6 to 2.5	A90RB	43	1.2
			2 to 1	A120SB	46	
			.8 to .45	A180TB	48	
			.4 to .35	A220UB	51	
	Over 275	Quenched and Tempered	4 to 12	A100KV	7000	6 0
			13 to 27	A150KV	7500	
			28 to 63	A220MV	8500	
			64 to 80	A240PV	9000	
			6 to 2.5	A100KV	36	1.8
			2 to 1	A150KV	38	
			.8 to .45	A220MV	43	
			.4 to .35	A240PV	46	

See section 16 for Cutting Fluid Recommendations
See section 20 for additional information

8.14 Thread Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	THREADS PER INCH / PITCH (P) mm	WHEEL IDENTIFICATION ANSI / ISO	WHEEL SPEED fpm / m/s	WORK SPEED fpm / m/min
13. STAINLESS STEELS, WROUGHT						
Ferritic						
405 434	135 to 185	Annealed	4 to 12	A90RB	8500	4.0
409 436			13 to 27	A120KV	9000	
429 442			28 to 63	A180TB	9500	
430 446			64 to 80	A220UB	10000	
			6 to 2.5	A90RB	43	1.2
			2 to 1	A120KV	46	
			.8 to .45	A180TB	48	
			.4 to .35	A220UB	51	
Austenitic						
201 304L 310S 330	135 to 275	Annealed or Cold Drawn	4 to 12	A90RB	8500	4.0
202 305 314 347			13 to 27	A120SB	9000	
301 308 316 348			28 to 63	A180TB	9500	
302 309 316L 384			64 to 80	A220UB	10000	
302B 309S 317 385			6 to 2.5	A90RB	43	1.2
304 310 321			2 to 1	A120SB	46	
			.8 to .45	A180TB	48	
			.4 to .35	A220UB	51	
Austenitic						
Nitronic 32	210 to 250	Annealed	4 to 12	A90RB	8500	4.0
Nitronic 33			13 to 27	A120SB	9000	
Nitronic 40			28 to 63	A180TB	9500	
Nitronic 50			64 to 80	A220UB	10000	
Nitronic 60			6 to 2.5	A90RB	43	1.2
			2 to 1	A120SB	46	
			.8 to .45	A180TB	48	
			.4 to .35	A220UB	51	
	320 to 375	Cold Drawn	4 to 12	A90RB	8500	4.0
			13 to 27	A120SB	9000	
			28 to 63	A180TB	9500	
			64 to 80	A220UB	10000	
			6 to 2.5	A90RB	43	1.2
			2 to 1	A120SB	46	
			.8 to .45	A180TB	48	
			.4 to .35	A220UB	51	
Martensitic						
403 440A	135 to 275	Annealed	4 to 12	A90RB	8500	4.0
410 440B			13 to 27	A120SB	9000	
414 440C			28 to 63	A180TB	9500	
420 501			64 to 80	A220UB	10000	
422 502			6 to 2.5	A90RB	43	1.2
431			2 to 1	A120SB	46	
Greek Ascoloy			.8 to .45	A180TB	48	
			.4 to .35	A220UB	51	
	Over 275	Quenched and Tempered	4 to 12	A100KV	7000	6.0
			13 to 27	A150KV	7500	
			28 to 63	A220MV	8500	
			64 to 80	A240PV	9000	
			6 to 2.5	A100KV	36	1.8
			2 to 1	A150KV	39	
			.8 to .45	A220MV	46	
			.4 to .35	A240PV	46	

See section 16 for Cutting Fluid Recommendations
See section 20 for additional information

MATERIAL	HARD-NESS Bhn	CONDITION	THREADS PER INCH / PITCH (P) mm	WHEEL IDENTIFI-CATION ANSI / ISO	WHEEL SPEED fpm / m/s	WORK SPEED fpm / m/min
14. PRECIPITATION HARDENING STAINLESS STEELS, WROUGHT 15-5 PH AM-355 16-6 PH AM-363 17-4 PH Custom 450 17-7 PH Custom 455 17-14 Cu Mo HNM AF-71 PH 13-8 Mo AFC-77 PH 14-8 Mo Almar 362 (AM-362) PH 15-7 Mo AM-350 Stainless W	150 to 200	Solution Treated	4 to 12 13 to 27 28 to 63 64 to 80	A90RB A120SB A180TB A220UB	8500 9000 9500 10000	4.0
			6 to 2.5 2 to 1 .8 to .45 .4 to .35	A90RB A120SB A180TB A220UB	43 46 46 51	1.2
	275 to 440	Solution Treated or Hardened	4 to 12 13 to 27 28 to 63 64 to 80	A100KV A150KV A220MV A240PV	7000 7500 8500 9000	6.0
			6 to 2.5 2 to 1 .8 to .45 .4 to .35	A100KV A150KV A220MV A240PV	36 38 43 46	1.8
15. CARBON STEELS, CAST **Low Carbon** ASTM A426 Grade CP1 1010 1020 **Medium Carbon** ASTM A352 Grades LCA, LCB, LCC ASTM A356 Grade 1 1030 1040 1050	100 to 300	Annealed, Normalized, Normalized and Tempered, or Quenched and Tempered	4 to 12 13 to 27 28 to 63 64 to 80	A90RB A120SB A180TB A220UB	8500 9000 9500 10000	4.0
			6 to 2.5 2 to 1 .8 to .45 .4 to .35	A90RB A120SB A180TB A220UB	43 46 46 51	1.2
	Over 50 R_C	Carburized and/or Quenched and Tempered	4 to 12 13 to 27 28 to 63 64 to 80	A100KV A150KV A220MV A240PV	7000 7500 8500 9000	6.0
			6 to 2.5 2 to 1 .8 to .45 .4 to .35	A100KV A150KV A220MV A240PV	36 38 43 46	1.8
16. ALLOY STEELS, CAST **Low Carbon** ASTM A27 Grade WC9 ASTM A352 Grades LC3, LC4 ASTM A426 Grades CP2, CP5, CP5b, CP11, CP12, CP15, CP21, CP22 1320 2320 4120 8020 2315 4110 4320 8620 **Medium Carbon** ASTM A27 Grades N1, N2, U-60-30 60-30, 65-35, 70-36, 70-40 ASTM A148: Grades 80-40, 80-50, 90-60, 105-85, 120-95, 150-125, 175-145 ASTM A216, Grades WCA, WCB, WCC ASTM A217, Grades WC1, WC4, WC5, WC6 ASTM A352 Grades LC1, LC2, LC2-1 ASTM A356, Grades 2, 5, 6, 8, 9, 10 ASTM A389 Grades C23, C24 ASTM A486 Classes 70, 90, 120 (materials continued on next page)	150 to 400	Annealed, Normalized, Normalized and Tempered, or Quenched and Tempered	4 to 12 13 to 27 28 to 63 64 to 80	A90RB A120SB A180TB A220UB	8500 9000 9500 10000	4.0
			6 to 2.5 2 to 1 .8 to .45 .4 to .35	A90RB A120SB A180TB A220UB	43 46 46 51	1.2
	Over 50 R_C	Carburized and/or Quenched and Tempered	4 to 12 13 to 27 28 to 63 64 to 80	A100KV A150JV A220MV A240PV	7000 7500 8500 9000	6.0
			6 to 2.5 2 to 1 .8 to .45 .4 to .35	A100KV A150JV A220MV A240PV	36 38 43 46	1.8

See section 16 for Cutting Fluid Recommendations
See section 20 for additional information

8.14 Thread Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	THREADS PER INCH / PITCH (P) mm	WHEEL IDENTIFI-CATION ANSI / ISO	WHEEL SPEED fpm / m/s	WORK SPEED fpm / m/min
16. ALLOY STEELS, CAST (cont.) **Medium Carbon (cont.)** (materials continued from preceding page) ASTM A487 Classes 1N, 2N, 4N, 6N, 8N, 9N 10N, 0N, 1Q, 2Q, 4Q, 4QA, 6Q, 7Q, 8Q 9Q, 10Q 1330 4130 80B30 8640 1340 4140 8040 9525 2325 4330 8430 9530 2330 4340 8440 9535 4125 8030 8630						
17. TOOL STEELS, CAST **Group I** ASTM A597 Grades CA-2, CH-12, CH-13, CO-1, CS-5	50 R_C max	Annealed or Quenched and Tempered	4 to 12 13 to 27 28 to 63 64 to 80 6 to 2.5 2 to 1 0.8 to .45 0.5 to .35	A90RB A120SB A180TB A220UB A90RB A120SB A180TB A220UB	8500 9000 9500 10000 43 46 48 51	4.0 1.2
	50 R_C to 58 R_C	Quenched and Tempered	4 to 12 13 to 27 28 to 63 64 to 80 6 to 2.5 2 to 1 0.8 to .45 0.5 to .35	A100KV A150JV A220MV A240PV A100KV A150JV A220MV A240PV	7000 7500 8500 9000 36 36 43 46	6.0 1.8
	Over 58 R_C	Quenched and Tempered	4 to 12 13 to 27 28 to 63 64 to 80 6 to 2.5 2 to 1 0.8 to .45 0.5 to .35	A100KV A150JV A240MV A280PV A100KV A150JV A240MV A280PV	7000 7500 8500 9000 36 36 43 46	6.0 1.8
Group II ASTM A597 Grades CD-2, CD-5	200 to 250	Annealed	4 to 12 13 to 27 28 to 63 64 to 80 6 to 2.5 2 to 1 0.8 to .45 0.5 to .35	A90RB A120SB A180TB A220UB A90RB A120SB A180TB A220UB	8500 9000 9500 10000 43 46 48 51	4.0 1.2
	48 R_C to 56 R_C	Quenched and Tempered	4 to 12 13 to 27 28 to 63 64 to 80 6 to 2.5 2 to 1 0.8 to .45 0.5 to .35	A100KV A150JV A220MV A240PV A100KV A150JV A220MV A240PV	7000 7500 8500 9000 36 36 43 46	6.0 1.8

See section 16 for Cutting Fluid Recommendations
See section 20 for additional information

MATERIAL	HARD-NESS Bhn	CONDITION	THREADS PER INCH / PITCH (P) mm	WHEEL IDENTIFI-CATION ANSI / ISO	WHEEL SPEED fpm / m/s	WORK SPEED fpm / m/min
17. TOOL STEELS, CAST (cont.) **Group II (cont.)** (materials listed on preceding page)	Over 56 R_C	Quenched and Tempered	4 to 12	A100KV	7000	60
			13 to 27	A150JV	7500	
			28 to 63	A240MV	8500	
			64 to 80	A280PV	9000	
			6 to 2.5	A100KV	36	7.6
			2 to 1	A150JV	38	
			.8 to .45	A240MV	43	
			.4 to .35	A280PV	46	
18. STAINLESS STEELS, CAST **Ferritic** ASTM A217 Grades C5, C12 ASTM A296 Grades CB-30, CC-50, CE-30, CA6N, CA-6NM, CD4MCu ASTM A297: Grade HC ASTM A487, Class CA6NM ASTM A608 Grade HC30	135 to 185	Annealed	4 to 12	A90RB	8500	40
			13 to 27	A120SB	9000	
			28 to 63	A180TB	9500	
			64 to 80	A220UB	10000	
			6 to 2.5	A90RB	43	12
			2 to 1	A120SB	46	
			.8 to .45	A180TB	48	
			.4 to .35	A220UB	51	
Austenitic ASTM A296 Grades CF-3, CF-3M, CF-8, CF-8C, CF-8M, CF-16F, CF-20, CG-8M, CG-12, CH-20, CK-20, CN-7M, CN-7MS ASTM A297: Grades HD, HE, HF, HH, HI, HK, HL, HN, HP, HT, HU ASTM A351: Grades CF-3, CF-3A, CF-3M, CF-3MA, CF-8, CF-8A, CF-8C, CF-8M, CF-10MC, CH-8, CH-10, CH-20, CK-20, CN-7M, HK-30, HK-40, HT-30 ASTM A451: Grades CPF8A, CPF3, CPF3A, CPF3M, CPF8, CPF8C, CPF8C (Ta Max), CPF8M, CPF10MC, CPH8, CPH10, CPH20, CPK20 ASTM A452, Grades TP 304H, TP 316H, TP 347H ASTM A608: Grades HD50, HE35, HF30, HH30, HH33, HI35 HK30, HK40, HL30, HL40, HN40, HT50, HU50	135 to 210	Annealed, Normalized or As Cast	4 to 12	A90RB	8500	40
			13 to 27	A120SB	9000	
			28 to 63	A180TB	9500	
			64 to 80	A220UB	10000	
			6 to 2.5	A90RB	43	12
			2 to 1	A120SB	46	
			.8 to .45	A180TB	48	
			.4 to .35	A220UB	51	
Martensitic ASTM A217, Grade CA-15 ASTM A296 Grades CA-15, CA-15M, CA-40 ASTM A426, Grades CP7, CP9, CPCA15 ASTM A487: Classes CA15a, CA-15M	135 to 225	Annealed, Normalized or Normalized and Tempered	4 to 12	A90RB	8500	40
			13 to 27	A120SB	9000	
			28 to 63	A180TB	9500	
			64 to 80	A220UB	10000	
			6 to 2.5	A90RB	43	12
			2 to 1	A120SB	46	
			.8 to .45	A180TB	48	
			.4 to .35	A220UB	51	

See section 16 for Cutting Fluid Recommendations
See section 20 for additional information

8.14 Thread Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	THREADS PER INCH / PITCH (P) mm	WHEEL IDENTIFI-CATION ANSI	WHEEL SPEED fpm	WORK SPEED fpm
18. STAINLESS STEELS, CAST (cont.) **Martensitic (cont.)** (materials listed on preceding page)	Over 275	Quenched and Tempered	4 to 12 13 to 27 28 to 63 64 to 80	A100KV A150JV A220MV A240PV	7000 7500 8500 9000	6 0
19. PRECIPITATION HARDENING STAINLESS STEELS, CAST ASTM A351. Grade CD-4MCu ACI Grade CB-7Cu ACI Grade CD-4MCu 17-4 PH AM-355	325 to 450	Solution Treated or Solution Treated and Aged	4 to 12 13 to 27 28 to 63 64 to 80	A90RB A120SB A180TB A220UB	8500 9000 9500 10000	4.0
21. GRAY CAST IRONS **Ferritic** ASTM A48· Class 20 SAE J431c Grade G1800 **Pearlitic- Ferritic** ASTM A48· Class 25 SAE J431c: Grade G2500 **Pearlitic** ASTM A48· Classes 30, 35, 40 SAE J431c Grade G3000 **Pearlitic + Free Carbides** ASTM A48 Classes 45, 50 SAE J431c: Grades G3500, G4000 **Pearlitic or Acicular + Free Carbides** ASTM A48: Classes 55, 60	45 R_C max	As Cast, Annealed or Quenched and Tempered	4 to 12 13 to 27 28 to 63 64 to 80	A90RB A120SB A180TB A220UB	8500 9000 9500 10000	4 0
	45 R_C to 52 R_C	As Cast, Annealed or Quenched and Tempered	4 to 12 13 to 27 28 to 63 64 to 80	A90RB A120SB A180TB A220UB	8500 9000 9500 10000	4 0
Austenitic (NI-RESIST) ASTM A436 Types 1, 1b, 2, 2b, 3, 4, 5, 6	100 to 250	As Cast	4 to 12 13 to 27 28 to 63 64 to 80	A90RB A120SB A180TB A220UB	8500 9000 9500 10000	4.0
22. COMPACTED GRAPHITE CAST IRONS	185 to 255	As Cast	4 to 12 13 to 27 28 to 63 64 to 80	A90RB A120SB A180TB A220UB	8500 9000 9500 10000	4 0

See section 16 for Cutting Fluid Recommendations
See section 20 for additional information

MATERIAL	HARD-NESS Bhn	CONDITION	THREADS PER INCH / PITCH (P)	WHEEL IDENTIFI-CATION ANSI	WHEEL SPEED fpm	WORK SPEED fpm
23. DUCTILE CAST IRONS						
Ferritic			4 to 12	A90RB	8500	
ASTM A536. Grades 60-40-18, 65-45-12			13 to 27	A120SB	9000	
SAE J434c. Grades D4018, D4512	52 R_C max	Annealed As Cast, Normalized and Tempered or Quenched and Tempered	28 to 63	A180TB	9500	4 0
Ferritic- Pearlitic			64 to 80	A220UB	10000	
ASTM A536: Grade 80-55-06			[illegible]	[illegible]	[illegible]	[illegible]
SAE J434c: Grade D5506						
Pearlitic- Martensitic						
ASTM A536. Grade 100-70-03						
SAE J434c: Grade D7003						
Martensitic						
ASTM A536: Grade 120-90-02						
SAE J434c: Grade DQ&T						
Austenitic (NI-RESIST Ductile)			4 to 12	A90RB	8500	
ASTM A439. Types D-2, D-2B D-2C, D-3, D-3A, D-4, D-5, D-5B	120 to 275	Annealed	13 to 27	A120SB	9000	4.0
ASTM A571: Type D-2M			28 to 63	A180TB	9500	
			64 to 80	A220UB	10000	
24. MALLEABLE CAST IRONS						
Ferritic			4 to 12	A90RB	8500	
ASTM A47: Grades 32510, 35018			13 to 27	A120SB	9000	
ASTM A602: Grade M3210	52 R_C max	Malleablized or Malleablized and Heat Treated	28 to 63	A180TB	9500	4 0
SAE J158. Grade M3210			64 to [illegible]	A220UB	10000	
Pearlitic						
ASTM A220. Grades 40010, 45006, 45008, 50005						
ASTM A602 Grade M4504, M5003						
SAE J158 Grades M4504, M5003						
Tempered Martensite						
ASTM A220. Grades 60004, 70003, 80002, 90001						
ASTM A602: Grades M5503, M7002, M8501						
SAE J158: Grades M5503, M7002, M8501						
36. NICKEL ALLOYS, WROUGHT AND CAST			4 to 12	A90RB	8500	
Nickel 200			13 to 27	A120SB	9000	
Nickel 201	80 to 170	Annealed or Cold Drawn	28 to 63	A180TB	9500	4 0
Nickel 205			64 to 80	A220UB	10000	
Nickel 211						
Nickel 220						
Nickel 230						
MONEL Alloy 400			4 to 12	A90RB	8500	
MONEL Alloy 401			13 to 27	A120SB	9000	
MONEL Alloy 404	115 to 240	Annealed, Cold Drawn or Cast	28 to 63	A180TB	9500	4 0
MONEL Alloy R405			64 to 80	A220UB	10000	
ASTM A296 Grades CZ-100, M-35						
ASTM A494 Grades CZ-100, M-35						

See section 16 for Cutting Fluid Recommendations
See section 20 for additional information

8.14 Thread Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	THREADS PER INCH / PITCH (P) mm	WHEEL IDENTIFI-CATION ANSI / ISO	WHEEL SPEED rpm / m/s	WORK SPEED rpm / m/min
36. NICKEL ALLOYS, WROUGHT AND CAST (cont.) DURANICKEL Alloy 301 MONEL Alloy 502 MONEL Alloy K500 NI-SPAN-C Alloy 902 PERMANICKEL Alloy 300	150 to 320	Solution Treated	4 to 12 13 to 27 28 to 63 64 to 80	A90PV A120SB A180TB A220UB	6000 9000 9500 10000	4.0
			6 to 2.5 2.5 to 1 1 to .45 .4 to .35	A90RB A120SB A180TB A220UB	43 46 48 51	1.2
	330 to 360	Aged	4 to 12 13 to 27 28 to 63 64 to 80	A90RB A120SB A180TB A220UB	8500 9000 9500 10000	4.0
			6 to 2.5 2.5 to 1 1 to .45 .4 to .35	A90RB A120SB A180TB A220UB	43 46 48 51	1.2
37. BERYLLIUM NICKEL ALLOYS, WROUGHT AND CAST†† Berylco 440 Berylco 41C Berylco 42C Berylco 43C Brush Alloy 200C Brush Alloy 220C Brush Alloy 260C	200 to 250	As Cast or Solution Treated	4 to 12 13 to 27 28 to 63 64 to 80	A90RB A120SB A180TB A220UB	8500 9000 9500 10000	4.0
			6 to 2.5 2.5 to 1 1 to .45 .4 to .35	A90RB A120SB A180TB A220UB	43 46 48 51	1.2
	283 to 425	Hardened or Aged	4 to 12 13 to 27 28 to 63 64 to 80	A90RB A120SB A180TB A220UB	8500 9000 9500 10000	4.0
			6 to 2.5 2.5 to 1 1 to .45 .4 to .35	A90RB A120SB A180TB A220UB	43 46 48 51	1.2
	47 R_C to 52 R_C	Hardened or Aged	4 to 12 13 to 27 28 to 63 64 to 80	A120JV A180KV A240MV A320PV	7000 7500 8500 9000	6.0
			6 to 2.5 2.5 to 1 1 to .45 .4 to .35	A120JV A180KV A240MV A320PV	36 38 43 46	1.8

See section 16 for Cutting Fluid Recommendations
See section 20 for additional information

††CAUTION Toxic Material, refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions

MATERIAL	HARD-NESS Bhn	CONDITION	THREADS PER INCH / PITCH (P) inch	WHEEL IDENTIFI-CATION ANSI / ISO	WHEEL SPEED fpm / m/s	WORK SPEED fpm / m/min
39. HIGH TEMPERATURE ALLOYS, WROUGHT AND CAST						
Nickel Base, Wrought						
AF2-1DA — Inconel Alloy 751	200 to 290	Annealed or Solution Treated	4 to 12	A90SB	9000	1.5 to 4.0
			13 to 27	A100TB		
Astroloy — M252			28 to 63	A180TB		
Haynes Alloy 263 — Nimonic 75			64 to 80	A280TB		
Hi-102 — Nimonic 80			6 to 2.5	A90SB	46	45 to 12
Incoloy Alloy 901 — Nimonic 90			2 to 1	A100TB		
Incoloy Alloy 903 — Nimonic 95			0.8 to 0.45	A180TB		
Inconel Alloy 617 — Rene 41			0.4 to 0.25	A280TB		
Inconel Alloy 625 — Rene 63	300 to 475	Solution Treated and Aged	4 to 12	A90SB	9000	1.5 to 4.0
Inconel Alloy 700 — Rene 77			13 to 27	A100TB		
Inconel Alloy 702 — Rene 95			28 to 63	A180TB		
Inconel Alloy 706 — Udimet 500			64 to 80	A280TB		
Inconel Alloy 718 — Udimet 700			6 to 2.5	A90SB	46	45 to 12
Inconel Alloy 721 — Udimet 710			2 to 1	A100TB		
Inconel Alloy 722 — Unitemp 1753			0.8 to 0.45	A180TB		
Inconel Alloy X-750 — Waspaloy			0.4 to 0.25	A280TB		
Nickel Base, Wrought						
Hastelloy Alloy B	140 to 220	Annealed or Solution Treated	4 to 12	A90SB	9000	1.5 to 4.0
Hastelloy Alloy B-2			13 to 27	A100TB		
Hastelloy Alloy C			28 to 63	A180TB		
Hastelloy Alloy C-276			64 to 80	A280TB		
Hastelloy Alloy G			6 to 2.5	A90SB	46	45 to 12
Hastelloy Alloy S			2 to 1	A100TB		
Hastelloy Alloy X			0.8 to 0.45	A180TB		
Incoloy Alloy 804			0.4 to 0.25	A280TB		
Incoloy Alloy 825	240 to 310	Cold Drawn or Aged	4 to 12	A90SB	9000	1.5 to 4.0
Inconel Alloy 600			13 to 27	A100TB		
Inconel Alloy 601			28 to 63	A180TB		
Refractaloy 26			64 to 80	A280TB		
Udimet 630			6 to 2.5	A90SB	46	45 to 12
			2 to 1	A100TB		
			0.8 to 0.45	A180TB		
			0.4 to 0.25	A280TB		
Nickel Base, Wrought						
TD-Nickel‡‡	180 to 200	As Rolled	4 to 12	A90SB	9000	1.5 to 4.0
TD-Ni-Cr‡‡			13 to 27	A100TB		
			28 to 63	A180TB		
			64 to 80	A280TB		
			6 to 2.5	A90SB	46	45 to 12
			2 to 1	A100TB		
			0.8 to 0.45	A180TB		
			0.4 to 0.25	A280TB		

See section 16 for Cutting Fluid Recommendations
See section 20 for additional information

‡‡CAUTION Toxic Material refer to National Institute for Occupational Safety and Health (NIOSH) for Precautions

8.14 Thread Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	THREADS PER INCH / PITCH (P) mm	WHEEL IDENTIFI-CATION ANSI / ISO	WHEEL SPEED fpm / m/s	WORK SPEED fpm / m/min
39. HIGH TEMPERATURE ALLOYS, WROUGHT AND CAST (cont.) **Nickel Base, Cast** B-1900 GMR-235 GMR-235D Hastelloy Alloy B Hastelloy Alloy C Hastelloy Alloy D IN-100 (Rene 100) IN-738 IN-792 Inconel Alloy 713C Inconel Alloy 718 M252 MAR-M200 MAR-M246 MAR-M421 MAR-M432 Rene 80 Rene 125 SEL SEL 15 TRW VI A Udimet 500 Udimet 700 ASTM A296 Grades CW-12M, N-12M, CY-40 ASTM A297 Grades HW, HX ASTM A494. Grades N-12M-1, N-12M-2, CY-40, CW-12M-1, CW-12M-2 ASTM A608: Grades HW50, HX50	200 to 425	As Cast or Cast and Aged	4 to 12 13 to 27 28 to 63 64 to 80	A90SB A100TB A180TB A280TB	9000	1.5 to 4.0
			6 to 2.5 2 to 1 0.8 to .45 .4 to .35	A90SB A100TB A180TB A280TB	45	.45 to 1.2
Cobalt Base, Wrought AiResist 213 Haynes Alloy 25 (L605) Haynes Alloy 188 J-1570 MAR-M905 MAR-M918 S-816 V-36	180 to 230	Solution Treated	4 to 12 13 to 27 28 to 63 64 to 80	A90SB A100TB A180TB A280TB	9000	1.5 to 4.0
			6 to 2.5 2 to 1 0.8 to .45 .4 to .35	A90SB A100TB A180TB A280TB	45	.45 to 1.2
	270 to 320	Solution Treated and Aged	4 to 12 13 to 27 28 to 63 64 to 80	A90SB A100TB A180TB A280TB	9000	1.5 to 4.0
			6 to 2.5 2 to 1 0.8 to .45 .4 to .35	A90SB A100TB A180TB A280TB	45	.45 to 1.2

See section 16 for Cutting Fluid Recommendations.
See section 20 for additional information.

MATERIAL	HARD-NESS Bhn	CONDITION	THREADS PER INCH / PITCH (P) mm	WHEEL IDENTIFI-CATION ANSI / ISO	WHEEL SPEED fpm / m/s	WORK SPEED fpm / m/min
Cobalt Base, Cast AiResist 13 AiResist 215 FSX-414 HS-6 HS-21 HS-31 (X-40) HOWMET #3 MAR-M302 MAR-M322 MAR-M509 NASA Co-W-Re WI-52 X-45	220 to 290	As Cast or Cast and Aged	4 to 12 13 to 27 28 to 63 64 to 80	A90SB A100TB A180TB A280TB	9000	1.5 to 4.0
			6 to 2.5 2 to 1 .8 to .45 .4 to .35	A90SB A100TB A180TB A280TB	46	45 to 1.2
	290 to 425	As Cast or Cast and Aged	4 to 12 13 to 27 28 to 63 64 to 80	A90SB A100TB A180TB A280TB	9000	1.5 to 4.0
			6 to 2.5 2 to 1 .8 to .45 .4 to .35	A90SB A100TB A180TB A280TB	46	45 to 1.2
Iron Base, Wrought A-286 Discaloy Incoloy Alloy 800 Incoloy Alloy 800H Incoloy Alloy 801 Incoloy Alloy 802 N-155 V-57 W-545 16-25-6 19-9DL	180 to 230	Solution Treated	4 to 12 13 to 27 28 to 63 64 to 80	A90SB A100TB A180TB A280TB	9000	1.5 to 4.0
			6 to 2.5 2 to 1 .8 to .45 .4 to .35	A90SB A100TB A180TB A280TB	46	45 to 1.2
	250 to 320	Solution Treated and Aged	4 to 12 13 to 27 28 to 63 64 to 80	A90SB A100TB A180TB A280TB	9000	1.5 to 4.0
			6 to 2.5 2 to 1 .8 to .45 .4 to .35	A90SB A100TB A180TB A280TB	46	45 to 1.2
47. POWDER METAL ALLOYS **Irons** F-0000-N F-0000-P F-0000-R F-0000-S F-0000-T	50 to 67 500kg	As Sintered	4 to 12 13 to 27 28 to 63 64 to 80	A90RB A120SB A180TB A220UB	8500 9000 9500 10000	4.0
			6 to 2.5 2 to 1 .8 to .45 .4 to .35	A90RB A120SB A180TB A220UB	45 46 48 51	1.2
Steels F-0008-P F-0008-S F-0005-S FC-0205-S FC-0208-P FC-0208-S FC-0508-P	101 to 426	As Sintered or Heat Treated	4 to 12 13 to 27 28 to 63 64 to 80	A90RB A120SB A180TB A220UB	8500 9000 9500 10000	4.0
			6 to 2.5 2 to 1 .8 to .45 .4 to .35	A90RB A120SB A180TB A220UB	45 46 48 51	1.2
FC-1000-N FN-0205-S FN-0205-T FN-0405-R FN-0405-S FN-0405-T FX-1005-T FX-2008-T						

See section 16 for Cutting Fluid Recommendations.
See section 20 for additional information.

8.14 Thread Grinding

MATERIAL	HARD-NESS Bhn	CONDITION	THREADS PER INCH PITCH (P) mm	WHEEL IDENTIFI-CATION ANSI ISO	WHEEL SPEED fpm m/s	WORK SPEED fpm m/min
47. POWDER METAL ALLOYS (cont.)			4 to 12	A90RB	8500	
Stainless Steels			13 to 27	A120SB	9000	4.0
SS-303-R	107	As Sintered	28 to 63	A180TB	9500	
SS-304-R	to	or	64 to 80	A220UB	10000	
SS-316-R	285	Heat Treated	6 to 2.5	A90RB	43	
SS 410-R			2 to 1	A120SB	46	1.2
			.8 to .45	A180TB	48	
			.4 to .35	A220UB	51	
48. MACHINABLE CARBIDES			4 to 12	D240R100B1/8	4500	
Ferro-Tic			13 to 27	D320T100B1/8	5000	1.5
	68 R_C		28 to 63	D400V100B1/8	5500	
	to	Hardened	64 to 80	D400V100B1/8	6000	
	70 R_C	and	6 to 2.5	D240R100B1/8	23	
		Tempered	2 to 1	D320T100B1/8	25	.45
			.8 to .45	D400V100B1/8	28	
			.4 to .35	D400V100B1/8	30	
49. CARBIDES			4 to 12	D240R100B1/8	4500	
Titanium Carbide			13 to 27	D320T100B1/8	5000	1.5
Tungsten Carbide	89 R_A		28 to 63	D400V100B1/8	5500	
	to	—	64 to 80	D400V100B1/8	6000	
	94 R_A		6 to 2.5	D240R100B1/8	23	
			2 to 1	D320T100B1/8	25	.45
			.8 to .45	D400V100B1/8	28	
			.4 to .35	D400V100B1/8	30	
51. MAGNETIC ALLOYS			4 to 12	A120JV	7000	
Alnico I			13 to 27	A180KV	7500	6 0
Alnico II	45 R_C		28 to 63	A240MV	8500	
Alnico III	to	As Cast	64 to 80	A320PV	9000	
Alnico IV	58 R_C		6 to 2.5	A120JV	36	
Alnico V			2 to 1	A180KV	38	1.8
Alnico V-7			.8 to .45	A240MV	43	
Alnico XII			.4 to .35	A320PV	46	
Columax-5						
Hyflux Alnico V-7						

See section 16 for Cutting Fluid Recommendations
See section 20 for additional information.

SECTION 9

INTRODUCTION TO NONTRADITIONAL MACHINING

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INTRODUCTION TO NONTRADITIONAL MACHINING 9

NONTRADITIONAL MACHINING is a generic designation applied to those material removal processes that have recently emerged, have not been used extensively heretofore, or are new to the user. These processes are sometimes labeled nonconventional, layless or nonmechanical. The designation "nontraditional" reflects a high degree of personal bias, and its use depends upon the experiences of the individual

Thirty-one nontraditional machining processes have been selected for inclusion in this handbook. They have been grouped for discussion according to their primary energy mode: that is, Mechanical, Electrical, Thermal or Chemical, as shown in table 9-1. While many more nontraditional machining processes exist in laboratory use, these thirty-one represent those processes which have emerged from the laboratory since the early 1940's, are available or are in use commercially, and have machinability data and information which are available in the public domain.

Nontraditional processes provide manufacturing engineers with additional choices or alternatives to the traditional or conventional mechanical and abrasive material removal processes. Figure 9-1 and table 9-2 demonstrate the relationships among the conventional and the nontraditional machining processes with respect to surface roughness, dimensional tolerance and metal removal rate. It is important to note that carefully selected and properly applied nontraditional machining processes offer some unique capabilities and fresh opportunities for cost improvement in the field of material removal.

The state of the art for nontraditional machining processes is still in a period of rapid change. It can be expected, therefore, that many of the values, ranges and limitations expressed in the data presented can be exceeded. The data comprise publicly available information circa 1979. A check with knowledgeable process vendors is recommended before proceeding with or rejecting any of these material removal processes. The Machinability Data Center monitors developments and collects data for these processes Inquiries are welcomed.

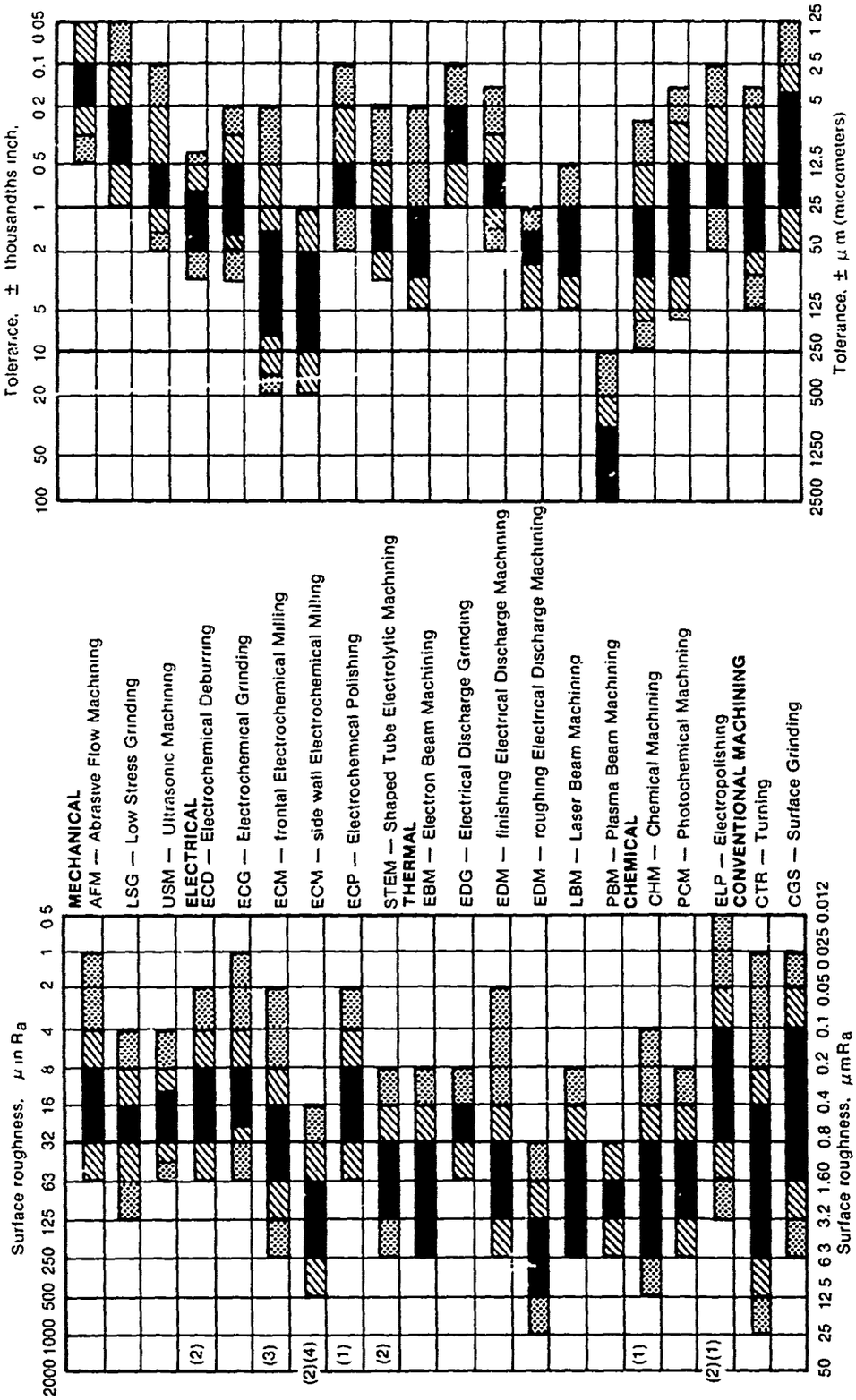
TABLE 9-1 Current Commercially Available Nontraditional Material Removal Processes

MECHANICAL
- AFM — Abrasive Flow Machining
- AJM — Abrasive Jet Machining
- HDM — Hydrodynamic Machining
- LSG — Low Stress Grinding
- RUM — Rotary Ultrasonic Machining
- TAM — Thermally Assisted Machining
- TFM — Total Form Machining
- USM — Ultrasonic Machining
- WJM — Water Jet Machining

ELECTRICAL
- ECD — Electrochemical Deburring
- ECDG — Electrochemical Discharge Grinding
- ECG — Electrochemical Grinding
- ECH — Electrochemical Honing
- ECM — Electrochemical Machining
- ECP — Electrochemical Polishing
- ECS — Electrochemical Sharpening
- ECT — Electrochemical Turning
- ES — Electro-stream™
- STEM™ — Shaped Tube Electrolytic Machining

THERMAL
- EBM — Electron Beam Machining
- EDG — Electrical Discharge Grinding
- EDM — Electrical Discharge Machining
- EDS — Electrical Discharge Sawing
- EDWC — Electrical Discharge Wire Cutting
- LBM — Laser Beam Machining
- LBT — Laser Beam Torch
- PBM — Plasma Beam Machining

CHEMICAL
- CHM — Chemical Machining
- ELP — Electropolish
- PCM — Photochemical Machining
- TCM — Thermochemical Machining (or TEM—Thermal Energy Method)



Notes:
(1) Depends on state of starting surface
(2) Titanium alloys are generally rougher than nickel alloys.
(3) High current density areas.
(4) Low current density areas.

Figure 9–1 Typical surface roughnesses and tolerances produced by nontraditional material removal production processes.

TABLE 9-2 Comparison of Material Removal Rates and Dimensional Tolerances for Conventional and Nontraditional Machining Processes

PROCESS	MAXIMUM RATE OF MATERIAL REMOVAL in³/min cm³/min	TYPICAL POWER CONSUMPTION hp/in³/min kW/cm³/min	CUTTING SPEED fpm m/min	PENETRATION RATE PER MINUTE in mm	ACCURACY ± ATTAINABLE in mm	ACCURACY ± AT MAXIMUM MATERIAL REMOVAL RATE in mm	TYPICAL MACHINE INPUT hp kW
Conventional Turning	200 3300	1 0.046	250 76	— —	0.0002 0.005	0.005 0.13	30 22
Conventional Grinding	50 820	10 0.46	10 3	— —	0.0001 0.0025	0.002 0.05	25 20
CHM	30 490	— —	— —	0.001 0.025	0.0005 0.013	0.003 0.075	— —
PBM	10 164	20 0.91	50 15	10 254	0.02 0.5	0.1 2.54	200 150
ECG	2 33	2 0.091	0.25 0.08	— —	0.0002 0.005	0.0025 0.063	4 3
ECM	1 16.4	160 7.28	— —	0.5 12.7	0.0005 0.013	0.006 0.15	200 150
EDM	0.3 4.9	40 1.82	— —	0.5 12.7	0.00015 0.004	0.002 0.05	15 11
USM	0.05 0.82	200 9.10	— —	0.02 0.50	0.0002 0.005	0.0015 0.040	15 11
EBM	0.0005 0.0082	10,000 455	200 60	6 150	0.0002 0.005	0.002 0.050	10 7.5
LBM	0.0003 0.0049	60,000 2,731	— —	4 102	0.0005 0.013	0.005 0.13	20 15

SECTION 10

MECHANICAL NONTRADITIONAL MACHINING OPERATIONS

10.1 Abrasive Flow Machining—AFM 10–3
10.2 Abrasive Jet Machining—AJM 10–15
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Abrasive Flow Machining—AFM 10.1

PROCESS SUMMARY

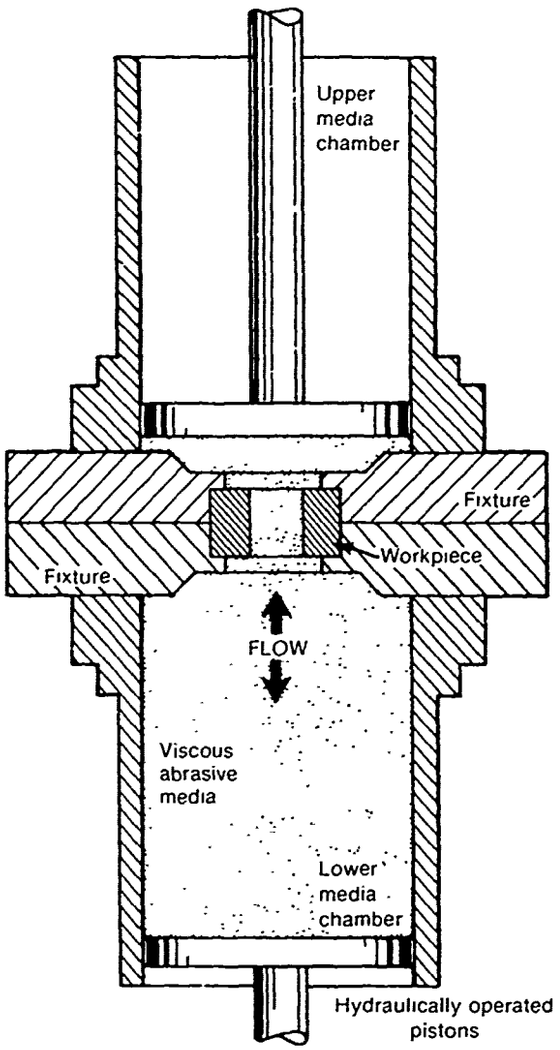


Figure 10.1–1 AFM schematic.

Principles

Abrasive flow machining (AFM) is the removal of material by a viscous, abrasive media flowing, under pressure, through or across a workpiece. Figure 10.1-1 contains a schematic presentation of the AFM process. The grit-loaded media of polymeric-base material is selected for its viscosity and type and proportion of grit, in order to suit the part shape and the intended action—deburring, polishing, radiusing. Generally, the putty-like media is extruded through or over the workpiece with motion usually in both directions using from one to one hundred flow reversals per fixture load. Aluminum oxide, silicon carbide, boron carbide or diamond abrasives are used. The velocity of the extruded media is dependent upon the principal parameters of viscosity, pressure, passage size and length.

Practical Applications

Edge finishing, radiusing, deburring, polishing and minor surface material removal are accomplished with AFM. It is not a mass material removal process, but it is particularly useful for polishing or deburring inaccessible internal passages. Materials from soft aluminum to tough nickel alloys are being processed with AFM. Removal of undesired layers produced by thermal processes such as EDM, LBM, or nitriding is also achieved with AFM. Polishing can quickly improve 30- to 300-microinch R_a [0.8 to 7.6 μm] finishes to one-tenth of the original roughness. Radii from 0.001 inch [0.025 mm] to 0.060 inch [1.5 mm] can be produced. Holes smaller than 1/64-inch [0.4 mm] diameter are sometimes difficult to process with AFM. Blind-hole polishing is impractical because AFM requires flowing media.

Operating Parameters

TABLE 10.1-1 Typical Values for AFM Operating Parameters

Media	
viscosity:	Stiff to fluid (see tables 10.1-2 and 10.1-4)
grit size:	= 8 to = 1000 (see table 10.1-3)
starting temperature:	90° to 125°F [32° to 52°C]
grit types:	See table 10.1-2
Flow	
pressure:	100 to 3000 psi [700 to 20,000 kPa]
volume:	3 to 100 fluid ounces [100 to 3000 ml]
rate.	2 to 60 gal/min [7 to 225 L/min]
Strokes	1 to 100

Material Removal Rates and Tolerances

The greatest material removal action will occur at the point(s) of maximum flow restriction. AFM processing times frequently range from one to five minutes. Stock removal can be uniform within 10 percent of the stock removed and uniform within each passageway, but out-of-roundness will not be corrected. Production rates of 1000 pieces per hour for multiple-fixtured small parts have been achieved. Usually only a few thousandths inch of material are removed by AFM, as demonstrated in tables 10.1-5 and 10.1-6. Where passageways of dissimilar size are adjacent, stock removal will also be dissimilar, but fixture design can sometimes provide compensation.

10.1 Abrasive Flow Machining—AFM

Surface Technology

Surface roughness to 2 microinches R_a [0.05 μm] can be obtained and dimensional tolerances to a few ten-thousandths inch can be achieved. Control of the volume of media flow is of major importance to quality control. Surfaces are typically smoothed to 1/10 the prior roughness, in terms of microinches R_a. Unidirectional lay is evident after a few strokes of the machine. No metal smearing results from the AFM process. Action occurs on both the peaks and the valleys on the surface. The abrading action can leave residual stresses under 0.001-inch deep [0.025 mm] in the surface layers. Surface layers altered by prior processes are smoothly removed by AFM.

Equipment and Tools

Low-, medium- and high-pressure systems are available in a range from 100 to 3000 psi [700 to 20,000 kPa]. Tooling is usually needed to direct, confine or sometimes control the flow paths. Hardened steel tooling directs the flow so that the major restriction occurs where material removal is desired. Ceramic or urethane inserts can minimize the tool wear that is experienced in some cases.

Many types of abrasives and viscosities are available as media. Media viscosity relates directly to the size of the restricting passage to be abraded. Fundamentally, viscosity must be high enough to maintain "extrusion-type" flow and high enough to hold the abrasive grains at the outermost surface of the extruding "slug" with sufficient force to allow the abrasive to cut the edges and/or surfaces of the restricting passage. At the same time, the media must be soft enough to flow at a reasonable rate, at the extrusion pressure available, in order to perform the finishing operation in an acceptable cycle time.

Machining Characteristics

More uniform deburring than can be accomplished with hand tools is a significant quality advantage for AFM. Careful post-operation cleaning is recommended. This cleaning can readily be accomplished by an air blast or immersion in an agitated solvent.

Machining action is gentle and continuous, and the burrs or "chips" are retained in the media. The media can tolerate as much as 10 percent of its volume in "chips" or foreign material. The media life is limited at the point at which a substantial number of the grains become dull. Reconditioning of the media can be accomplished by measured additions of abrasive grit and lubricant.

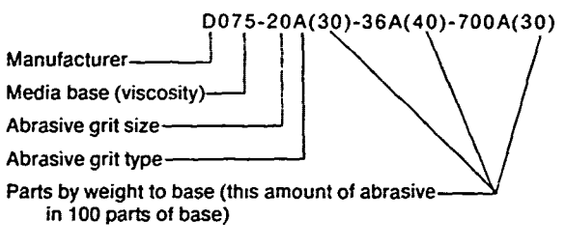
SELECTED DATA

TABLE 10.1-2 Abrasive Flow Media Designations

Viscosity Grade or Base*:
- LV or 500 — low
- LMV or 300 — low-medium
- MV or 200 — medium
- HMV or 100 — high-medium
- HV or 50 — high

Grit Type*:
- A — Aluminum oxide
- B — Boron carbide
- C — Silicon carbide (in ANSI B74.13 standard)
- D — Diamond
- S — Silicon carbide (in some manufacturers' nomenclatures)

Media Nomenclature (One system):



*Number and letter codes are not necessarily of equal viscosity—see manufacturers recommendations.
*See section 3.14 for grit hardness

TABLE 10.1-3 Grit Sizes Used in AFM

GRIT SIZE	AVERAGE PARTICLE SIZE	
	in	μm
8	0.1817	4,615
10	0.1366	3,470
12	0.1003	2,550
14	0.0830	2,110
16	0 0655	1,660
20	0 0528	1,340
25	0.0408	1,035
30	0.0365	925
35	0.0280	710
45	0.0200	508
50	0.0170	432
60	0.0160	406
70	0.0131	328
80	0.0105	267
90	0 0085	216
100	0 0068	173
120	0.0056	142
140	0.0048	122
170	0.0034	86
200	0.0026	66
230	0.00248	63
270	0.00175	44
325	0.00128	33
400	0.00090	23
500	0.00073	19
600	0.00057	14
800	0.00044	11
900	0.00038	10
1,000	0.00032	8

TABLE 10.1-4 Guide to Media Selection
(Viscosity grades for passageways with 2:1 length-to-width ratio)

PASSAGE WIDTH		EXTRUSION PRESSURE		
in	mm	Low	to	High
1/64	0.4			LV*
1/32	0.8		LV	LMV
1/16	1.6		LV LMV	MV
1/8	3.2	LV	LMV MV	HMV
1/4	6.4	LMV	MV HMV	HV
1/2	12.8	MV	HMV HV	
1	25.4	HMV	HV	
2	50.8	HV		

SOURCE Extrude Hone Corporation

NOTES As usable media extrusion pressure increases higher viscosity media grades may be used

If passage length is substantially shorter than two times passage width higher viscosity media or lower extrusion pressure may be used

If passage length is substantially longer than two times passage width lower viscosity media or higher extrusion pressures may be required

Media *slug flow* rates affect uniformity of stock removal and edge radius size

Slow *slug flow* rates (speed of abrasive *slug* passing through restricting passage) are best for uniformly removing material on close tolerance parts

High *slug flow* rates produce larger edge radii

*See table 10.1-2 for explanation of viscosity grade codes

TABLE 10.1-5 AFM Cutting Test Results for Cold Rolled Steel Discs—10 Full-Reverse Cycles

Conditions:
- hole length ..... 0.25 inch [6.25 mm]
- hole diameter ..... 0.125 inch [3.18 mm] nominal—initially
- number full reverse cycles 10
- equipment ..... Dynetics HL15
- initial media temperature ..... 30°C (86°F)

Media (moderately fast):
- base polymer 100 (high-medium viscosity) 56.5%
- 36-grit size, white aluminum oxide (A) or black silicon carbide (S) or boron carbide (B) 37.8%
- 700-grit size, black silicon carbide (S) 5.7%

MEDIA GRIT TYPE	PRESSURE psi	TOTAL TIME min	INITIAL DIAMETER inch	FINAL DIAMETER inch	INCREASE inch	RADIUS inch	STOCK REMOVAL milligrams
Aluminum oxide	300	18.0	0.127	0.141	0.014	0.020	118
	400	3.8	0.127	0.145	0.018	0.020	176
	500	1.8	0.127	0.153	0.026	0.040	293
Silicon carbide	300	22.7	0.126	0.144	0.018	0.020	168
	400	4.2	0.127	0.149	0.022	0.025	239
	500	2.0	0.127	0.153	0.026	0.030	293
Boron carbide	300	19.3	0.126	0.160	0.034	0.020	328
	400	3.8	0.125	0.164	0.039	0.020	344
	500	1.6	0.126	0.173	0.047	0.040	540

SOURCE: W. B. Perry, Properties and capabilities of low pressure abrasive flow mediae, Technical paper MR75-831, Society of Manufacturing Engineers, 1975.

TABLE 10.1-6 AFM Cutting Test Results for Cold Rolled Steel Discs—30 Full-Reverse Cycles

Conditions
- hole length ..... 0.25 inch [6.35 mm]
- hole diameter ..... 0.125 inch [3.18 mm] nominal—initially
- number of full reverse cycles 30
- equipment ..... Dynetics HL15
- initial media temperature ..... 25°C (77°F)
- media pressure ..... 450 psi [3100 k Pa]

Media
- base polymer 64.5%
- 60-grit size, black silicon carbide (S) 21.3%
- 700-grit size, black silicon carbide (S) 14.2%
- base polymer ..... 100, 200, 300 (see table 10.1-2 for viscosities)

or
- base polymer 56.5%
- 36-grit size, black silicon carbide (S) 37.8%
- 700-grit size, black silicon carbide (S) 5.7%
- base polymer ..... 100, 050 (see table 10.1-2 for viscosities)

MEDIA	TOTAL TIME min	INITIAL DIAMETER inch	FINAL DIAMETER inch	RADIUS inch
Size 60 grit, Base 300	4.0	0.125	0.136	0.045
Size 60 grit, Base 200	4.4	0.125	0.138	0.040
Size 60 grit, Base 100	7.7	0.126	0.153	0.020
Size 36 grit, Base 100*	4.1	0.125	0.189	0.040
Size 36 grit, Base 100*	1 6	0.249	0.267	0.055
Size 36 grit, Base 050	22 0	0.373	0.408	0 040

SOURCE: W B. Perry, Technical paper MR75-831, Society of Manufacturing Engineers, 1975.
* Same media as in table 10.1-5.

Stock Removal and Flow Rates[1]

One of the attractive features of AFM is the wide variety of available and easily adjustable process parameters. The effects of changing some of these parameters for specific media compositions are illustrated in figures 10 1-2 to 10.1-7. These data come from simple laboratory tests on cold-rolled-steel samples and are intended only to provide "guidelines" for use in actual production situations. The interrelationships of various parameters depend greatly on the characteristics of a given media composition. A few widely different media compositions were examined in order to formulate general rules that can be applied to AFM. Parameter relationships are also affected by the size and length of the flow passages. The data in figures 10.1-2 to 10.1-7 are limited to the examination of round holes machined normal to the test piece surfaces. The general rules which emerged are as follows:

1. Stock removal per unit time increases substantially with increasing extrusion pressure (figures 10.1-2 to 10.2-4).
2. Media flow rate increases with increasing extrusion pressure. Note: Flow rate increases proportionally with extrusion pressure, or logarithmically, as indicated in figure 10.1-5.
3. Flow rate increases as media temperature increases (figure 10.1-6). Note: In the tests conducted in preparing this graph, stock removal per unit volume of flow did not change with changes in flow velocity over the range covered by the graph.
4. Increasing hole length reduces both flow rate and diameter change per unit flow (figure 10.1-7).

These general rules apply for each of the medias examined, but the degree of application varies. These variances reflect differences in the content of base materials, lubricants and/or plasticizers as well as differences in the size and percentage of grit. The relative size and length of the flow passage also is likely to have an effect on these relationships.

[1]Based on text and figures from L J Rhoades, Extrude hone—edge and surface finishing—capabilities and costs, Technical paper MR77-366, Society of Manufacturing Engineers, Dearborn, MI, 1977

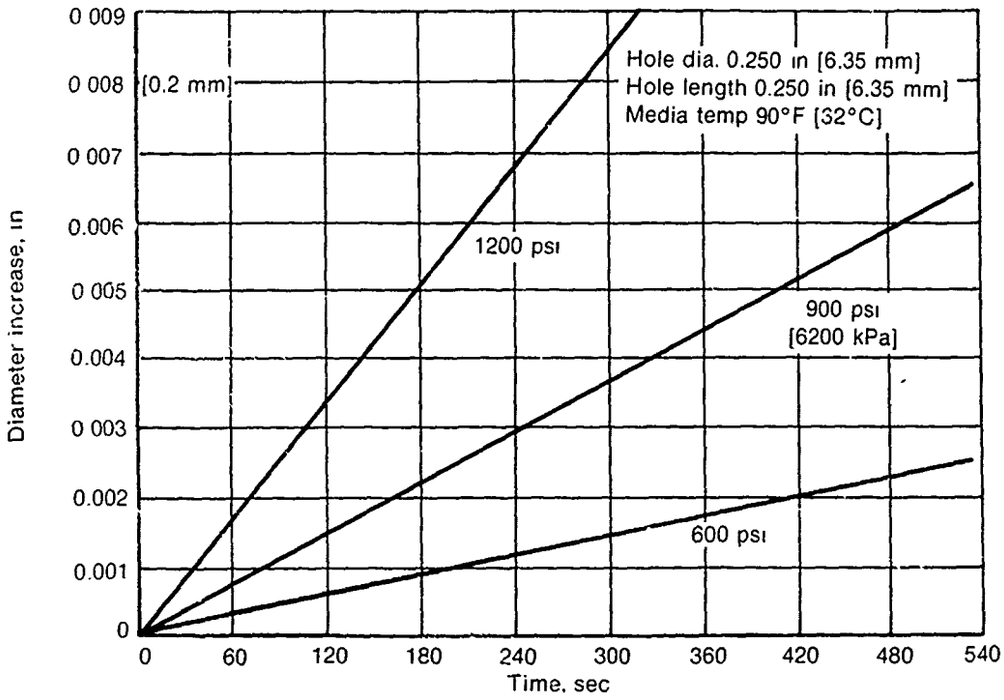


Figure 10.1-2 Stock removal rates for AFM of cold-rolled-steel samples using media 70 (633) at three extrusion pressures. (From L. J. Rhoades, Extrude hone-edge and surface finishing-capabilities and costs, Technical paper MR77-366, Society of Manufacturing Engineers, Dearborn, MI, 1977. p. 14)

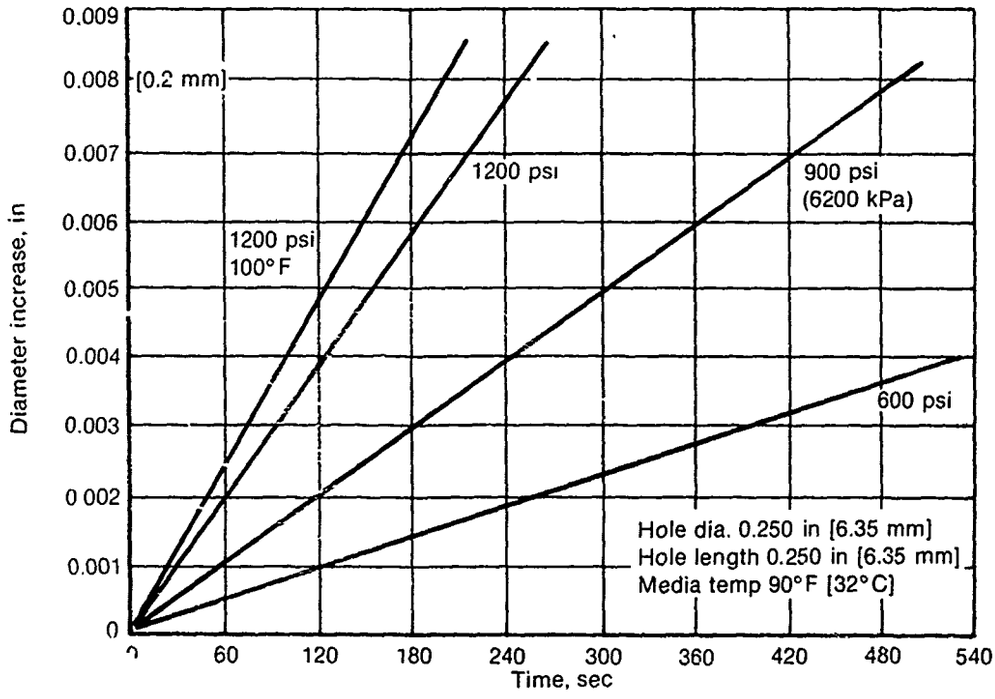


Figure 10.1-3 Stock removal rates for AFM of cold-rolled-steel samples using media 36 (564) at four extrusion pressures. (L. J. Rhoades, p. 14)

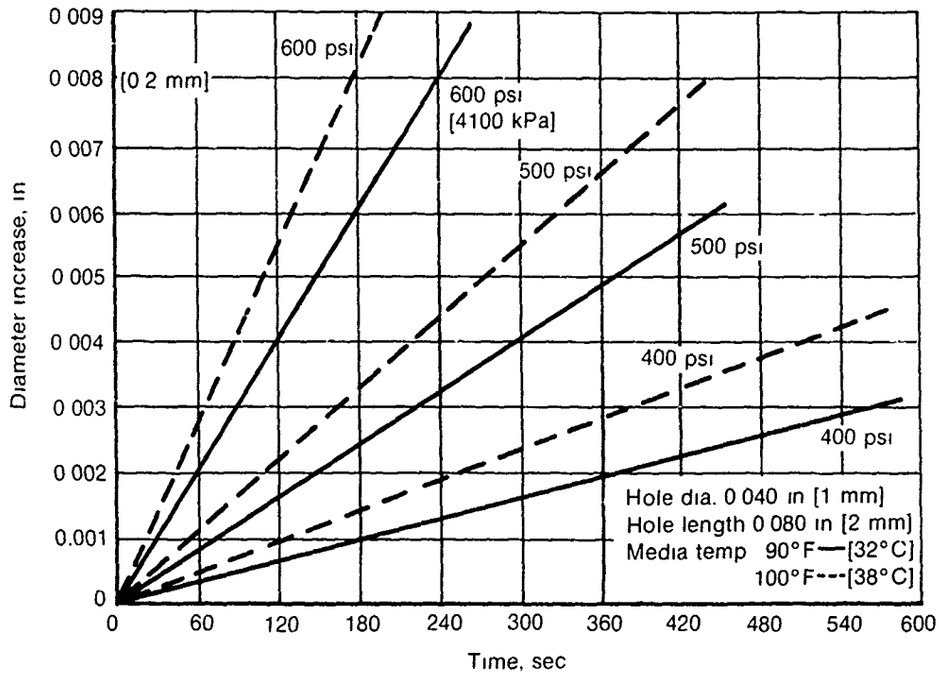


Figure 10.1–4 Stock removal rates for AFM of cold-rolled-steel samples using media 100 (356) at three extrusion pressures. (L J Rhoades, p 15)

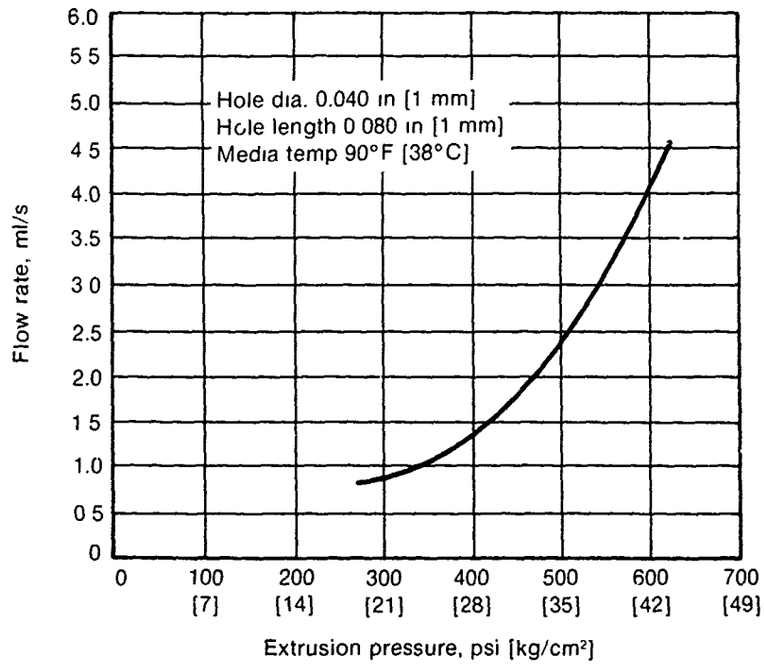


Figure 10.1–5 Media flow rate versus extrusion pressure. Test conditions same as figure 10.1–4 (L. J. Rhoades, p. 16)

10.1 Abrasive Flow Machining—AFM

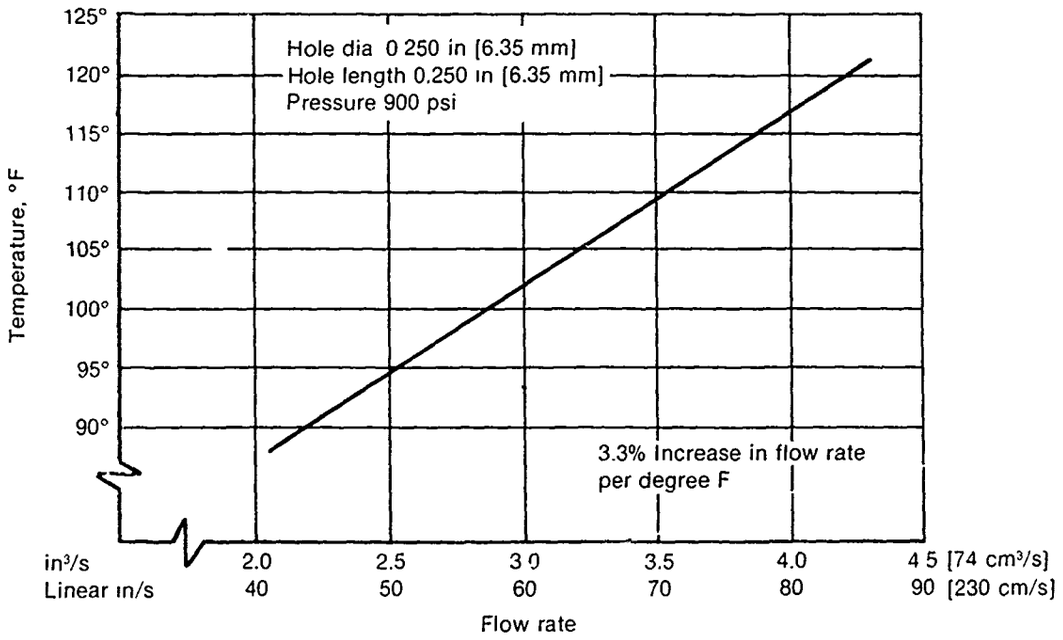


Figure 10.1-6 Media flow rate versus temperature for AFM of cold-rolled-steel samples using media 70 (633). (L. J. Rhoades, p. 16)

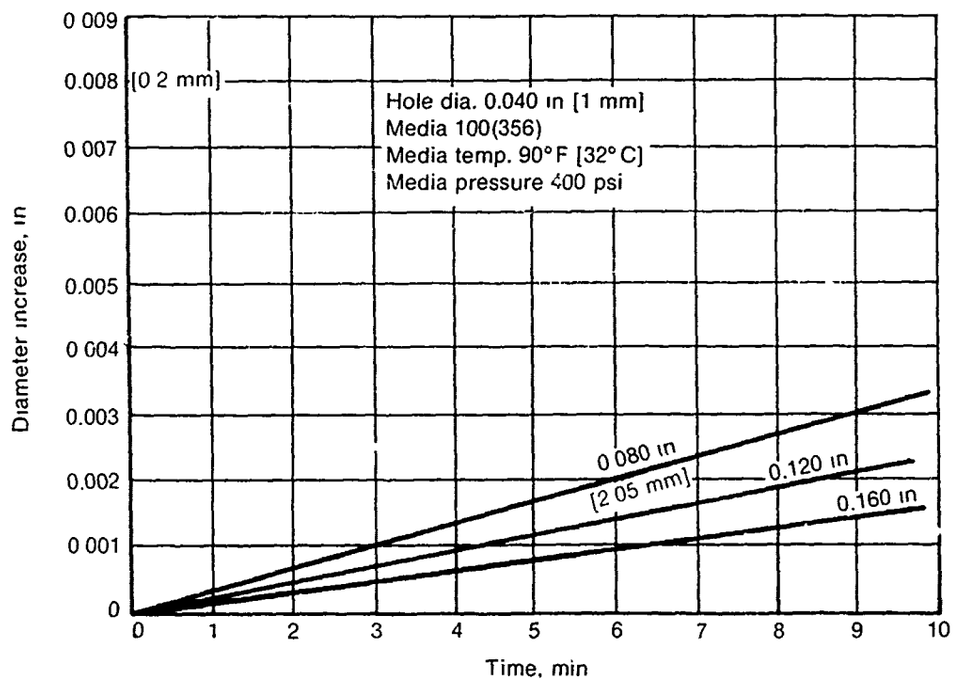


Figure 10.1-7 Stock removal rates for AFM of cold-rolled-steel samples with three hole lengths. (L. J. Rhoades, p. 15)

Hole Enlargement

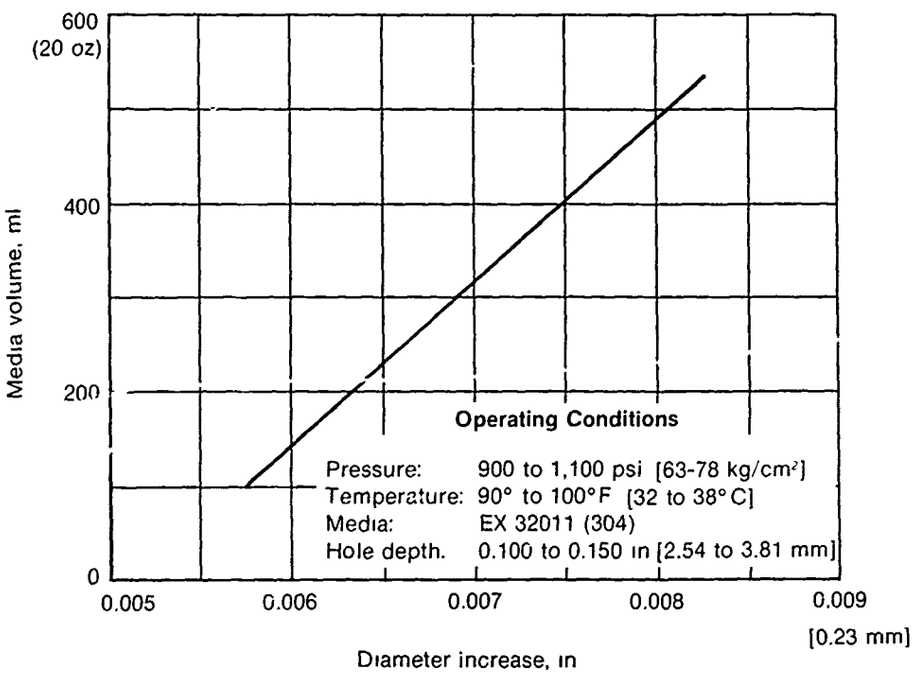


Figure 10.1-8 Hole diameter increase as a function of media volume. Data from enlarging 0.015-inch diameter laser drilled holes in a nickel alloy. (Courtesy of General Electric Company)

10.1 Abrasive Flow Machining—AFM

SPECIFIC APPLICATIONS DATA

TABLE 10.1–7 Specific Applications Data for Abrasive Flow Machining

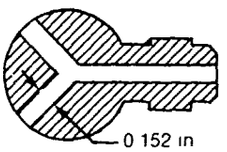
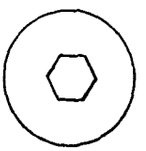
Work material	Stainless Steel	Hardened Die Steel	Tungsten Carbide
Workpiece configuration	 0 152 in Deburr 12 drilled hole intersections	 Radius & remove recast layer from extrusion die	 Draw die polishing
Media type	Dynetics D080-20S(50)-36S(50)-700S(40)	Extrude Hone MV70S	Extrude Hone HV30μD
grit type.	Silicon carbide	Silicon carbide	Diamond
grit size	50 parts-20 grit; 50 parts-36 grit, 40 parts-700 grit	70 grit	30 micron
volume	10-inch stroke	3 passages, 6,000 in³	1,500 in³
Pressure, psi.	450	450	800
Media temperature, °F.		80	110
Process time	90 s	4 min	3 to 8 min
Number strokes (one way)	6	20	30
Pieces per fixture:	1	1	1
Material removed (Dimension changed)	0.001 inch per surface	0.00075 inch per surface	0.001 to 0.002 inch
Surface roughness change, μin R_a	63 to 16	75 to 7	25-35 to 6-8

TABLE 10.1-7—Continued

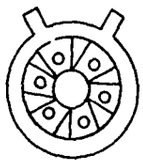
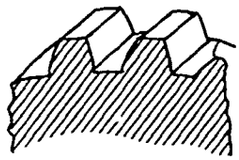
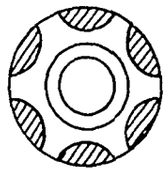
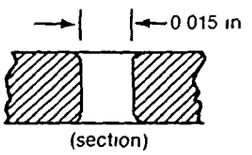
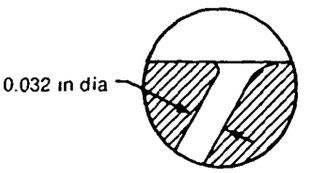
Work material.	Cast Stellite	High Strength Steel	AISI Type O2 Tool Steel
Workpiece configuration:	 Jet fuel swirler polish, radius & deburr	 Thread deburr	 Polished retainer seat pockets
Media type.	Dynetics D060-20B(35)-36B(35)-700(45)	Extrude Hone MV70S	Extrude Hone MV24S
grit type:	Boron carbide	Silicon carbide	Silicon carbide
grit size:	35 parts-20 grit; 35 parts-36 grit, 45 parts-700 grit	70 grit	24 grit
volume:	12-inch stroke	1,000 in^3	5,600 in^3
Pressure, psi:	450	600	1,400
Media temperature, °F:		80	
Process time:	3 min	2 min	7 min
Number strokes (one way):	6	4	14
Pieces per fixture:	3	1	1 (6 to 8 practical)
Material removed (Dimension changed):	Polished	0.0002 inch per surface	0.002 inch per surface
Surface roughness change, μin R_a:	↓3 to 12	40 to 8	100 to 10

TABLE 10.1-7—Continued

Work material.	**Cast Nickel Alloy**	**Cast Nickel Alloy**
Workpiece configuration·	 (section) Remove recast from small holes	 Removal of recast & add radii to hole
Media type.	Dynetics D250-220S(50)	Extrude Hone VLV320S
grit type:	Silicon carbide	Silicon carbide
grit size:	50 parts-220 grit	320 grit
volume:	1,000 ml	480 ml
Pressure, psi:	475	1,100
Media temperature, °F.	95	110
Process time:	Controlled by volume, not strokes and time	Controlled by volume, not strokes and time
Number strokes (one way):	Controlled by volume, not strokes and time	Controlled by volume, not strokes and time
Pieces per fixture:	1	1
Material removed (Dimension changed).	0.004 inch on diameter	0.005 inch on diameter
Surface roughness change, μin R_a:	50 to 16	—

PROCESS SUMMARY

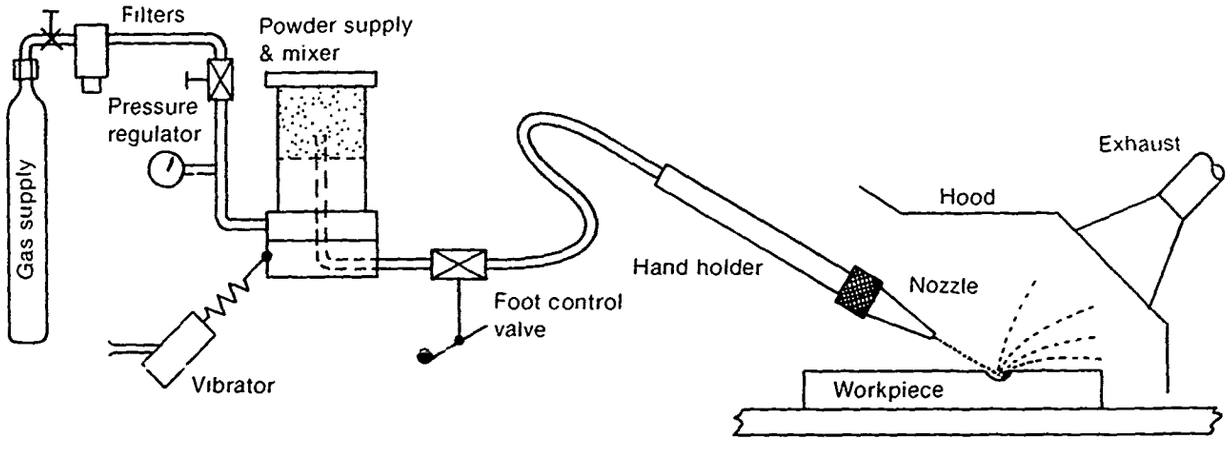


Figure 10.2–1 AJM schematic.

Principles

Abrasive jet machining (AJM) is the removal of material through the action of a focused, high velocity stream of fine grit or powder-loaded gas The gas should be dry, clean and under modest pressure. Figure 10.2-1 shows a schematic of the AJM process The mixing chamber sometimes uses a vibrator to promote a uniform flow of grit. The hard nozzle is directed close to the workpiece at a slight angle. The operation should be enclosed in a dust hood or be near an adequate exhaust collector. Cutting is controlled by type of abrasive, gas pressure, rate of abrasive flow, angle of and closeness of nozzle to workpiece, and duration of application. Masks of copper, glass or rubber are sometimes used to control overspray or the etching pattern.

Practical Applications

Cutting, deburring, cleaning, deflashing and etching of glass, ceramics, or hard metals can be accomplished with AJM. It may also be used for deburring of cross holes, slots, and threads in small precision parts that require a burr-free finish, such as hydraulic valves, aircraft fuel systems and medical appliances. Parts machined from nylon, Teflon*, and Delrin* may also be deburred. The cleaning of irregular surfaces, such as holes that break through threads, is one advantage of the ability of the abrasive stream to follow contours. Drilling holes in metal is not a viable application because the walls will have significant taper, and the drilling speed is very slow.

Hand-held nozzles, template guides, pantograph guides, or motorized fixtures are used for simple and intricate shapes or holes in sensitive, brittle, thin or difficult materials. Discs as small as 1/16-inch [1.6 mm] diameter and discs up to 1/4-inch [6.35 mm] thick have been cut in glass without the occurrence of chipping. Other good applications for AJM are insulation stripping and wire cleaning without affecting the conductor, and micro-deburring, as on hypodermic needles. Frosting glass, trimming circuit boards, and trimming silicon and gallium are routine. Removal of films and delicate cleaning, such as the removal of smudges from antique documents, is also possible. Hybrid circuit resistor and capacitor trimming is a typical production application in the electronics industry.

*Trademark E. I Du Pont de Nemours & Co., Inc.

10.2 Abrasive Jet Machining—AJM

Operating Parameters

TABLE 10.2-1 Typical Values for AJM Operating Parameters

Abrasive	
types	Aluminum oxide for aluminum and brass Silicon carbide for stainless steel and ceramic Bicarbonate of soda for nylon, Teflon*, Delrin* and light cleaning Glass beads for polishing
size·	10 to 150 μm, well classified and clean
quantity	1 to 5 g/min for fine work 5 to 10 g/min for usual cuts 10 to 20 g/min for heavier cuts
Carrier gas	
types·	Dry air, carbon dioxide, nitrogen, nitrous oxide, helium (Do *not* use oxygen)
quantity·	Up to 1 0 ft³/min [28 L/min]
pressure	30 to 190 psi [207 to 1,310 kPa]
velocity.	500 to 1,100 ft/s [152 to 335 m/s]
Nozzle	
material.	Tungsten carbide or sapphire
tip distanc (ntd) to wo..	^ 0 inches [2.54 to 76 mm] (see ;s 10 2-2 and 10 2-3
opening·	..r 0.005 to 0 046 inch [0 13 to 1.2 mm] Rectangular size 0.003 x 0.020 to 0.026 x 0 026 inch [0.075 x 0.50 to 0 65 x 0.65 mm]
operating angle:	Vertical to 60° off vertical

Material Removal Rates and Tolerances

AJM is ?ot a mass material removal process; it is a finishing pr ·s The typical removal rate for plate glass is 0.001 . inch per minute [16.4 mm³/min]. The speed of drilling ... ass is impressive; however, higher hardness ceramics cut at approximately 50 percent higher rates and metals cut at lesser rates, as low as 10 to 25 percent that of glass depending on the metal properties. Tumbling, vibratory or larger recirculating blast cabinets may be more practical for large parts. The rate of material removal is affected by several factors, including abrasive type and particle size, nozzle opening, nozzle-to-work-surface distance, nozzle angle, and particle velocity. Generally, the larger the particle and the higher the velocity, the faster the material removal.

Figure 10 2-4 illustrates the factors that can influence material removal. These data were taken on plate glass of 450 to 510 Knoop hardness using a 0 018-inch [0 46 mm] diameter nozzle, air as the gas at 75 psi [517 kPa], and 1/32-inch [0.79 mm] nozzle tip distance (ntd) from the workpiece (unless otherwise expressed) Silicon carbide abrasive would cut at approximately the same values

Because of the small amount of abrasive flowing through the nozzle, it is possible to be very selective in material removal The radius on holes, slots, grooves, and threads that are deburred abrasively will vary from sharp to 0 010 inch [0.25 mm] depending on abrasive used and blast time. It is common for micro-abrasive blasting to be a secondary deburring operation after rechasing threads, reaming holes, or using a wheel to remove the heaviest burrs. A practical minimum cut width is 0.005 inch [0.13 mm]. Tolerances are typically ±0.005 [±0.13 mm] with ±0.002 inch [±0.05 mm] possible with good fixturing and motion control. Taper is present in deep cuts.

Surface Technology

Surfaces generated by AJM have a random "grainness" or matte texture. Surface roughness ranges from 6 to 63 microinches R_a [0.15 to 1.6 μm] depending on grit size, as demonstrated in tables 10.2-2 and 10.2-3.

The AJM process is cool cutting; heat sensitive alloys are not affected. Constant motion of the nozzle is necessary to prevent unwanted grooves on the surface. Cleaning of the surfaces of softer materials may be necessary to remove any imbedded particles of grit. Cleaning is also required to remove grit from crevices or internal passageways in the workpiece.

Equipment and Tooling

The equipment consists of four parts: (1) an apparatus which stores, mixes and propels the abrasive; (2) a work chamber; (3) a dust collector; and (4) a dry gas supply. A complete system is available for a modest investment. Single- or dual-tank, bench-top apparatus is available. The work station should provide sufficient illumination for the operator. The dust collector should be a commercial unit of at least 3/4 horsepower with a cloth-bag filter that can handle fine powder particles as small as 40 microinches [1 μm]. The gas supply of at least 100 to 125 pounds per square inch [690 to 862 kPa] must be dried to a moisture content of less than 50 parts per million. It is possible to use bottled carbon dioxide or nitrogen as a dry gas supply.

The nozzle tips are normally made of tungsten carbide. Their life will vary depending on the type of abrasive and the operating pressure used. Tip life of 8 to 15 hours with silicon carbide and 20 to 35 hours with aluminum oxide is reasonable.

Abrasive powder must be clean, dry, and very well classified. It is not practical to reuse abrasive powder because contamination and worn grit will cause a decline in cutting rates.

Machining Chacteristics

The powders used in AJM are nontoxic. but adequate dust control is needed Silica dust produced during AJM may be a health hazard Commercial grades of abrasive powders are not suitable for AJM because they are not classified closely enough to assure proper flow and they may contain some silica dust. Ordinary shop air should not be used without adequate filtration to remove moisture and oil. Oxygen should never be used as the propelling gas because it may produce a violent chemical reaction when combined with the workpiece chips or the abrasive.

SELECTED DATA

TABLE 10.2–2 Surface Roughness for Glass Processed with AJM

ABRASIVE TYPE	GRIT SIZE		SURFACE ROUGHNESS	
	μin	μm	μin R_a	μm R_a
Aluminum oxide	400	10	6 to 8	0.15 to 0.20
	1100	28	14 to 20	0.36 to 0.51
	2000	50	38 to 55	0.97 to 1.40

TABLE 10.2–3 Surface Roughness for 316 Stainless Steel (Annealed) Processed with AJM

(Initial surface was ground to 18.5 μin R_a [0.47 μm])

ABRASIVE TYPE	GRIT SIZE		SURFACE ROUGHNESS	
	μin	μm	μin R_a	μm R_a
Aluminum oxide	400	10	8 to 20	0.20 to 0.50
	1000	25	10 to 21	0.25 to 0.53
	2000	50	15 to 38	0.38 to 0.96
Silicon carbide	800	20	12 to 20	0.30 to 0.50
	2000	50	17 to 34	0.43 to 0.86
Glass bead	2000	50	12 to 38	0.30 to 0.96

SOURCE: Comco Incorporated.

ORIFICE mm	NOZZLE CUTTING PATTERN, mm Nozzle Tip Distance, mm						
	0.38	0.79	1.59	2.38	3.18	4 76	6 35
0.46 dia	0.48 dia	0.81 dia	0.89 dia	1.22 dia	1.32 dia	1 90 dia	2 24 dia
0.51 x 0.15	0.66 x 0.33	0.76 x 0.48	0.96 x 0.71	1.12 x 0.76	1.22 x 1.22	1 42 x 1 40	1.80 x 1 70
1.02 x 0.15	1.22 x 0.38	1.40 x 0.61	1.60 x 1.02	1.73 x 1 19	2.06 x 1.60	2.49 x 2.18	2.72 x 2 64
1.52 x 0.15	1.62 x 0.25	1.73 x 0.41	1.88 x 0.64	2.11 x 0.91	2.21 x 1.04	2.49 x 2.18	2.72 x 2.64
2.54 x 0.15	2.67 x 0.38	2.82 x 0.64	3.12 x 1.02	3.20 x 1.14	3.30 x 1.17	3 53 x 1.52	3.89 x 1.88
3.81 x 0.15	3.96 x 0.41	4.01 x 0.56	4.24 x 0.81	4.37 x 1.01	4.57 x 1.37	4.93 x 1 78	5 23 x 2 18

Figure 10.2–2 Cutting pattern of nozzle versus nozzle tip distance. (Data courtesy of S. S. White Industrial Products)

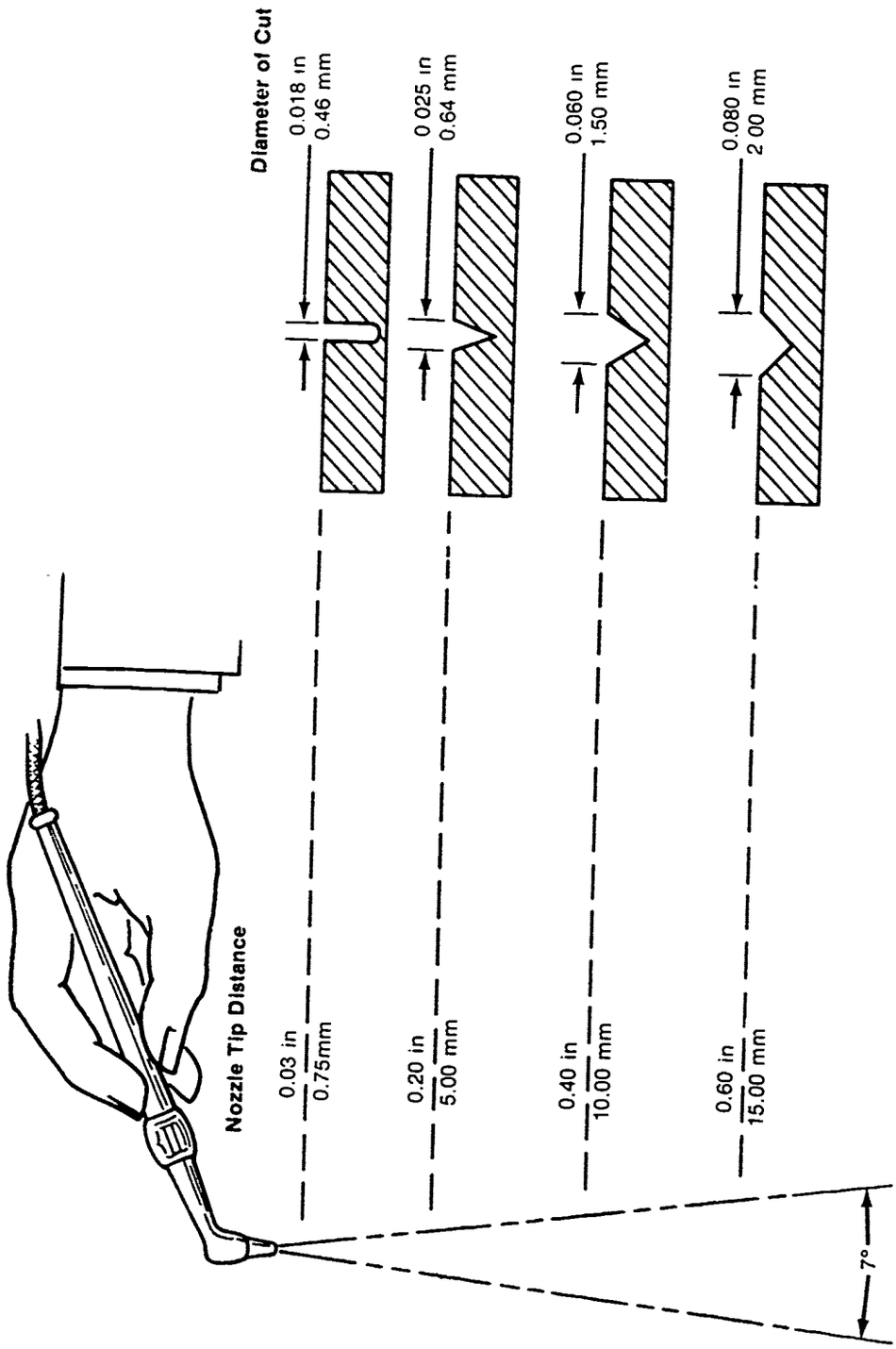
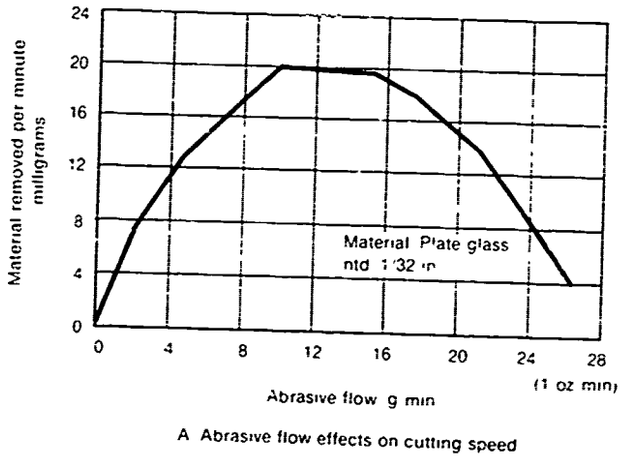
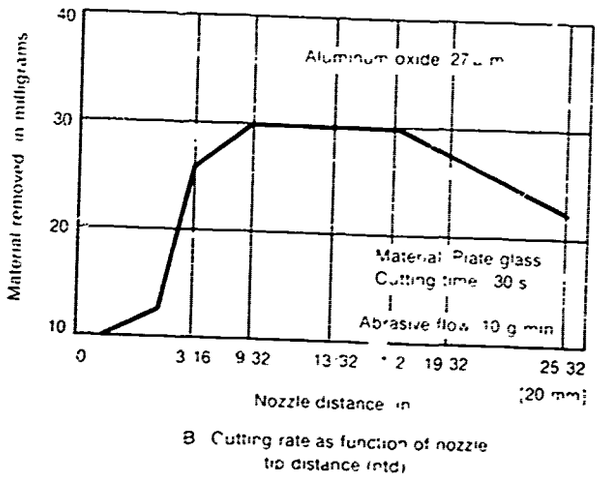


Figure 10.2–3 Typical cutting action of 0.018 inch [0.46 mm] diameter nozzle. (Data courtesy of S. S. White Industrial Products)

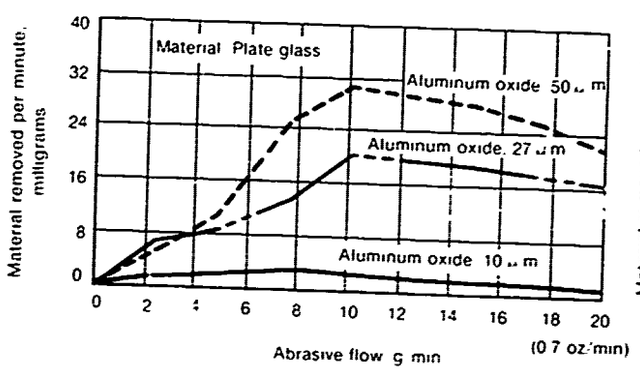
10.2 Abrasive Jet Machining—AJM



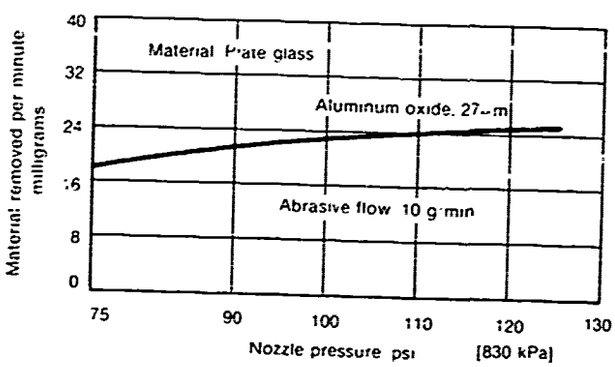
A Abrasive flow effects on cutting speed



B Cutting rate as function of nozzle tip distance (ntd)



C Effect of grit size on cutting speed



D Effect of gas pressure on cutting speed

Figure 10.2–4 Factors affecting material removal rates for AJM. (Adapted from W. Kulischenko, Abrasive jet machining techniques and related AJM equipment, Technical paper MR68-524. Society of Manufacturing Engineers, Dearborn, MI, 1968, pp. 4–5)

PROCESS SUMMARY

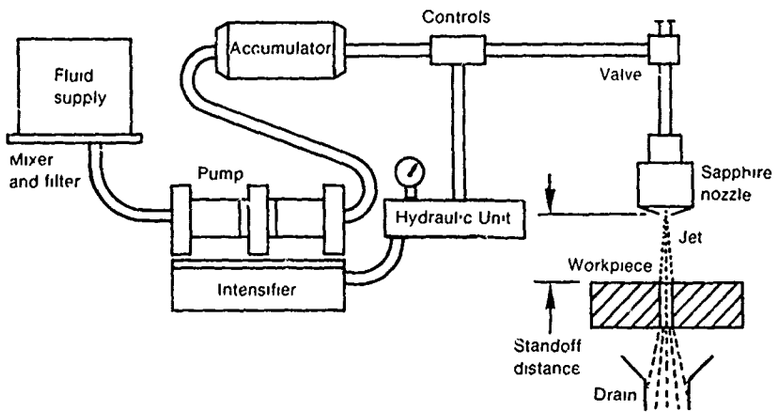


Figure 10.3–1 HDM schematic.

Principles

Hydrodynamic machining (HDM) removes material by the impingement of a high-velocity fluid against the workpiece (see figure 10.3–1). The coherent jet of water or water with additives (to aid coherence or prevent freezing) is propelled at speeds up to Mach 3 thereby cutting or shearing the workpiece. A synthetic-sapphire nozzle controls the jet stream and establishes the standoff distance which is important for controlling the cutting depth. Relatively small volumes of fluid are used. The fluid is pumped to the desired operating pressure aided by a hydraulically driven intensifier and an accumulator tank smooths out the pulses. The cut can be initiated at any point on the workpiece and the kerf (width of cut) is insensitive to dwell of the jet. The "chips" enter the exit stream. The power density in the stream can reach 6.5 x 10^8 watts per square inch [10^{10} watts/mm^2].

Practical Applications

The ability of HDM to cut very thin, soft metals or nonmetallic materials in any position with a very narrow kerf leads to many form-cutting applications, such as those described in tables 10.3–3, 10.3–4 and 10.3–5. A cutting or deburring action can be initiated at any point on the workpiece. HDM can be substituted for a carbide slitting saw. Since it is a non-dulling tool, HDM can produce a better edge cut. The narrow kerf can result in material and cost savings. The low level cutting temperatures allow the processing of wood and paper products, such as cutting 3/4-inch [19 mm] acoustic ceiling tile at 250 feet per minute [76 m/min] using a 45,000 pounds per square inch [310 MPa] jet. HDM has been used to cut furniture forms of 1/2 inch [12.5 mm] laminated paperboard, 1/2-inch [12.5 mm] asbestos brake shoe linings and 3/4-inch [19 mm] thick shoe sole material. Some work has been done with thin, mild steel; however, cutting of hard metals is still experimental using pressures above 100,000 pounds per square inch [700 MPa]. Scribing of maskants for chemical machining is a productive application.

Operating Parameters

TABLE 10.3–1 Typical Values for HDM Operating Parameters

Fluid	
type:	Water or water plus additives—well filtered
additives:	Glycerine, polyethylene oxide, long-chain polymers
pressure:	10 to 60 ksi [69 to 415 MPa]
jet velocity:	1,000 to 3,000 ft/s [305 to 915 m/min] (figure 10.3–4)
flow:	Up to 2 gal/min [7.5 L/min] (figure 10.3–5)
jet force on workpiece:	1 to 30 lb [4.5 to 134 N] (figure 10.3–4)
Power:	Up to 50 hp [38 kW] available; figures 10.3–4, 10.3–5, 10.3–6, 10.3–14
Cutting rates—traverse rates:	See table 10.3–2 and figures 10.3–7, 10.3–9, 10.3–10, 10.3–11
Nozzle	
material:	Synthetic sapphire most common, also hardened steels, 17-4 stainless
diameter:	0.003 to 0.015 inch [0.075 to 0.38 mm]
angle:	Perpendicular to positive rake angles of 30° (figures 10.3–2 and 10.3–18)
Kerf width:	0.003 to 0.016 inch [0.075 to 0.41 mm]
Standoff distance:	0.1 to several inches [2.5 to 50 mm]; ¼ inch [3 mm] is typical (see figures 10.3–16 and 10.3–17)

10.3 Hydrodynamic Machining—HDM

General Observations

- Increasing nozzle diameter improves performance and increases horsepower requirements (figure 10.3-12)
- Increasing pressure increases penetration, quality of cut and horsepower requirements.
- Lower pressure reduces edge quality and delamination effects
- Traverse rates are directly related to cost and rates of production.
- Increased standoff distance decreases penetration and increases noise (figures 10.3-16 and 10.3-17).
- Additives can increase cutting performance and reduce cut width (figures 10.3-16 and 10.3-17)
- Smaller nozzles produce finer cuts.
- Larger nozzles are needed for slicing thicker materials.
- Lower traverse rates improve the quality of cut.
- Cutting performance can improve with positive rake angles.

Material Removal Rates and Tolerances

Cutting rates depend on the work material (table 10.3-4) and vary directly with the horsepower applied and inversely with the material thickness. Rates up to 6,000 feet per minute (1,830 m/min) have been attained on paper products. Slots and through cuts are common. Removal rates for various materials are shown in figures 10.3-7 to 10.3-13. The lack of sensitivity to dwell allows contours to be controlled to an accuracy limited only by the machine elements. The kerf is about 0.001-inch (0.025 mm) larger than the orifice utilized. For composite materials, the best combination is a high-pressure jet from a small nozzle operating at a slight rake angle and close to the workpiece. Taper can be a factor if too large of a standoff distance is used.

Surface Technology

Edge quality depends upon how easily the workpiece fractures. Soft materials cut smoothly and crushable materials can be slit with high quality edges. Test cuts are recommended before selecting the final operating parameters. The high energy density of the jet stream causes a slight rise in temperature which may melt some types of plastics at low traverse rates, but the temperature is not high enough to be a concern for paper-type materials. Tendency to delaminate layers of composite materials during cutting can be eliminated by reducing the cutting rate.

Equipment and Tools

Machine and hydraulic components are available for HDM; however, a general-purpose machine tool is not regularly available. Each application is engineered to meet the requirements as found by sample test cuts made to determine the exact values for the key operating parameters. Equipment generating pressures up to 60,000 pounds per square inch (415 MPa) is commercially available with controls, filters and hydraulic seals of reasonable durability. A drain and sump need to be provided close to the workpiece. The jet stream does not dull and nozzle life is respectable, provided there is good filtration of the fluid. Filtration down to 0.5 micrometer (20 μin) followed by demineralization and deionization is recommended to reduce erosion of the nozzle. There is little frictional drag in the cut and virtually no forces at right angles to the jet; therefore, holding-fixture requirements are minimal. Multiple jets have been arranged for multiple cuts.

Use of NC or CNC is helpful with HDM. Recent equipment has reached 4-by-5-foot (1.2 x 1.5 m) table size with speeds of 15 inches per second (380 mm/s) and acceleration to top speed in 0.2 second.

Machining Characteristics

The "chips" mix in the fluid so dust is eliminated; therefore, explosion and fire hazards are reduced. Air entrapped in the jet stream can create considerable noise with some work materials. The noise level increases with standoff distance but can be reduced by using certain fluid additives or certain rake angles. The noise levels are generally below the OSHA requirements. Periodic preventive maintenance is very desirable for equipment operating at these pressures.

SELECTED DATA

There are several valid techniques for selecting operating parameters for HDM The steps in table 10 3-2 are recommended as one logical sequence Supporting data come from the other figures and tables in accordance with the terms as explained in figure 10.3-3

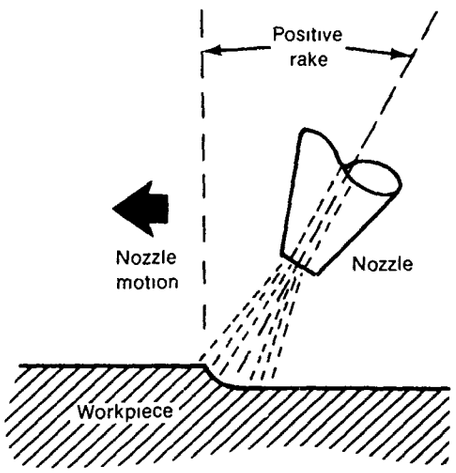


Figure 10.3-2 HDM nozzle angles.

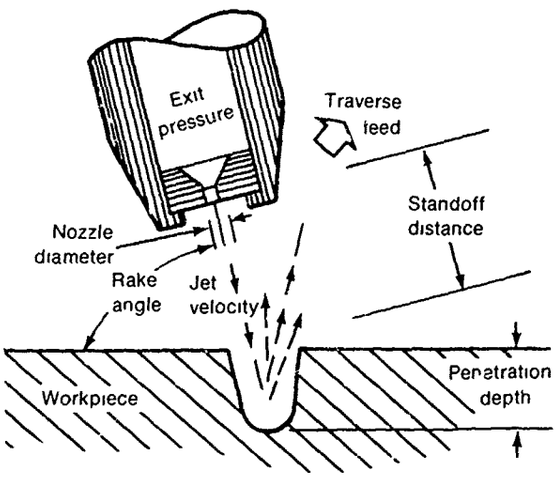


Figure 10.3-3 HDM parameter terminology.

TABLE 10.3-2 Steps To Select HDM Operating Parameters

1	Can workpiece material be machined by HDM?	Tables 10 3-3, 10 3-4 and 10.3-5
2	Cutting rates required	User's process or production requirements
3	Nozzle size and pressure	Test cuts or table 10 3-4, figures 10.3-7, 10 3-8, 10.3-13 Pressure is usually less than 65 ksi [450 MPa]. Nozzle size is approximately 0 001 inch [0 025 mm] less than cut width.
4	Cutting rates	Table 10.3-4 and figures 10.3-7, 10.3-9, 10 3-10, 10.3-11 Rate is approximately inversely proportional to thickness being cut
5	Flow rate	Figure 10.3-5
6	Power	Figure 10 3-5 or 10 3-6
7.	Standoff distance	0 to 0.5 inch [0 to 0.13 mm], smallest distance is best
8	Rake angle (straight-line cutting only)	Figures 10.3-2, 10.3-16, 10.3-17, 10.3-18
9	Fluid additives	Figures 10.3-16 and 10 3-17
10.	Confirm parameters selected Check surface quality, wetting, and kerf width for acceptability	Trial cut of specimen material.

10.3 Hydrodynamic Machining—HDM

TABLE 10.3-3 Partial List of Materials Successfully Cut with HDM
(With some maximum thickness of cut)

Abrasives—coated papers, cloth
Acoustic tile
Acrylic plastics
Aluminum
Aluminum honeycomb
Asbestos brake linings
Asphalt base materials

Bakery products
Boron-aluminum composite
Boron-epoxy composite
Boron-polyester composite
Box board
Brake linings
Brass

Carbon bricks and electrodes
Carpets
Ceramic foam
Coal
Concrete
Copper
Cork

Delrin

Epoxy—Kevlar

Fabrics, automotive
Fabrics, "soft" materials (except doubleknit fabrics)
Fiberglass-epoxy composite
Fiberglass insulation—to 5-inch [125 mm] thickness
Fiberglass—Nomex core sandwich—to 0.75-inch [19 mm] thickness
Fiberglass reinforced phenolic—to 0.5-inch [12.5 mm] thickness
Firebrick
Food (frozen meats, vegetables)
Furniture components

Glass—polyimide
Glass fiber reinforced polyester
Graphite
Graphite-epoxy composite—to 0.625-inch [15.9 mm] thickness
Gypsum boards

Insulating materials

Kevlar and epoxy—to 0.5-inch [12.5 mm] thickness

Laminated plastics
Lead
Leathers
Lucite plate—to 0.5 inch-[12.5 mm] thickness

Maple
Micarta—to 0.37 inch [9.5 mm] thickness
Mild steel
Mineral fibers (acoustic tile)

Neoprene rubber, 50 Shore hardness—to 2-inch [50 mm] thickness
Nomex honeycomb—to 3-inch [75 mm] thickness
Nylon (brushes, carpets)

Oak

PVC
Paper—corrugated board, filters, impregnated, coated, laminated newsprint
Plastics
Plexiglass

Plywood—to 1-inch [25 mm] thickness
Poplar
Polycarbonate—to 0.25-inch [6 mm] thickness
Polyester fabrics and carpets
Polyethylene sheets
Polypropylene tubes
Polystyrene
Polyurethane foam—to 1-inch [25 mm] thickness

Rocks
Roofing (composition, asbestos, rolls, shingles)
Rubber (foams, reinforced shoe soling, tire tubes)

Shoe leather
Silicone rubber—to 2-inch [50 mm] thickness
Slag
Steel (mild and thin)
Styrofoam
Styrene foams
Suits
Synthetic rubber
Teflon—to 0.37-inch [9.5 mm] thickness

Urethane foams

Vinyl sheets
Vinyl edge foam—to 1-inch [25 mm] thickness

White granite
Wood (fiber tiles, fiber padding, particle board, paneling veneer)

TABLE 10.3–4 HDM Cutting Rates for Several Materials

MATERIAL	THICKNESS		NOZZLE DIAMETER		PRESSURE		CUTTING SPEED	
	in	mm	in	mm	bar	MPa	in/s	m/s
ABS plastic	0.11	2.8	0 003	0.075	2580	258	0 55	0.0142
Acoustic tile	0.75	19	0.010	0.25	3100	310	3200	82
Aluminum honeycomb	1	25	—	—	4200	420	33	0.85
Automotive carpet	1 layer	1 layer	—	—	4200	420	118	3
Automotive vinyl	13 layers	13 layers	—	—	4200	420	165	4.25
Boxboard (white lined chipboard)	0 016	0.4	0.005	0.125	1770	177	37.5	0.965
Boxboard (white lined chipboard)	0 025	0.635	0 005	0.125	1740	174	31.5	0.805
Boxboard (white lined chipboard)	0.035	0.89	0.005	0.125	2440	244	24	0.61
Brake shoe material	0.5	13	—	—	4200	420	16 4	0.42
Corduroy	14 layers	14 layers	—	—	4200	420	74	1.9
Cotton nylon fabric	50 layers	50 layers	—	—	4200	420	126	3.2
Crepe	100 layers	100 layers	—	—	4200	420	166	4.25
Delrin	0.1	2.5	0.015	0.38	4120	412	8	0.2
Ethyl polyvinyl chloride	0.125	3.2	—	—	3500	350	8	0.2
Fiberglass epoxy	0.139	3.55	0.010	0.25	4120	412	0.1	0.0025
Graphite epoxy	0.067	1.7	0.008	0.2	3800	380	1	0.025
Graphite epoxy	0.136	3.45	0.010	0.25	4120	412	0 5	0.0125
Graphite epoxy	0.273	6.9	0 014	0.35	4120	412	1.1	0.0275
Graphite epoxy prepreg	1 ply	1 ply	0.003	0.075	3800	380	39	1
Hardwood pulp sheet	—	—	0.004	0.1	2480	248	27 5	0.7
Kevlar epoxy	0.125	3.2	0.010	0.25	3800	380	0 5	0.0125
Kevlar epoxy	0.25	6.3	0 014	0.35	4120	412	0.8	0.0205
Leather	0.175	4.45	0.002	0.05	3030	303	0 35	0.0091
Newsprint	—	—	0.004	0.1	585	58.5	420	10.6
Nylon tire fabric	0 032	0.8	—	—	4200	420	166	4.25
Plywood	0.25	6.4	—	—	4200	420	67	1.7
Plexiglass	0.4	10	0.015	0.38	4120	412	2.7	0.07
Polycarbonate	0.2	5	0.015	0.38	4120	412	4	0.1
Polyethylene (high density)	0.12	3	0 002	0.05	2860	286	0.36	0.0092
Polypropylene gasket	1 6	40	—	—	4200	420	100	2.5
Polypropylene (40%) glass fiber	0.25	6.4	—	—	4200	420	16.6	0.42
Rubber belt (cotton reinforced)	—	—	0 002	0.05	2960	296	0.9	0.023
Styrene (high impact)	0.12	3	0.003	0.075	2480	248	0 25	0.0064
Tissue paper	2 ply	2 ply	—	—	1000	100	7100	180
Transite (asbestos cement)	0 75	19	0.010	0.25	3800	380	0.71	0.018
Wood veneer	0 1	2.5	—	—	4200	420	166	4.25

10.3 Hydrodynamic Machining—HDM

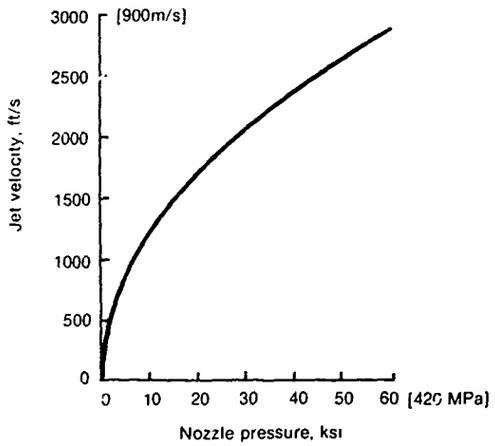
TABLE 10.3-5 Parameters for Hydrodynamic Machining of Various Nonmetallic Materials

MATERIAL	THICKNESS		NOZZLE OPENING		FEED RATE	
	in	cm	in	mm	in/min	m/min
Plywood	0.25	0.6	0 012	0.3	200	5
	0.37	0.95	0 012	0.3	100	2.5
	1.0	2.5	0.012	0.3	60	1.5
Foam rubber	0.5	1.27	0.008	0.2	1000 est.	25.4
	0.5	1.27	0.012	0.3	1000 est	25.4
	4.0	10.16	0.012	0.3	1000 est.	25.4
Neoprene, 50 Shore	0.5	1.27	0.012	0.3	600 est.	15.2
	2.0	5.08	0.012	0.3	100	2.5
Grey silicone rubber, 40 Shore	0.6	1.52	0.012	0.3	500 est	12.7
Fiberglass and epoxy	0.25	0.6	0 012	0.3	120	3
Fiberglass and phenolic	0.25	0.6	0.012	0.3	150	3.8
Circuit board	0.090	0.23	0.008	0.2	60	1.5
Fiberglass and Nomex core	0.5	1.27	0.012	0.3	360	9.1
	0.75	1.9	0.012	0.3	340	9
Nomex core only	2.0	5.08	0.012	0.3	300	7.6
Kevlar and epoxy	0.25	0.6	0.012	0.3	100	2.5
Graphite and epoxy	0.25	0.6	0.012	0.3	40	1
ABS	0.090	0.23	0.012	0.3	300	7.6
Polycarbonate	0.092	0.24	0.012	0.3	340	8.6

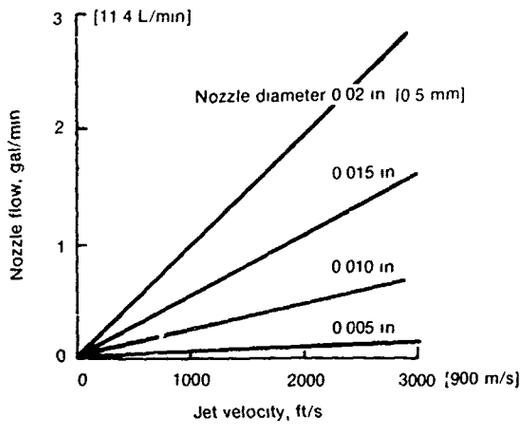
These feed rates can be extrapolated inversely on a nearly linear basis as the material thickness is reduced. That is, if a 0.25 inch [0.6 cm] thickness can be cut at 200 in/min [5 m/min], a 0.125 inch [0.3 cm] thickness can be cut at 400 in/min [10 m/min].

SOURCE. E. J. Buck and D L Zeulow, New techniques in water jet cutting, Technical paper MR79-376, Society of Manufacturing Engineers, Dearborn, MI, 1979, p. 5

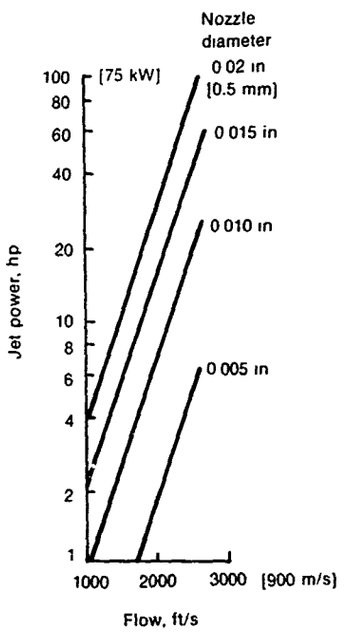
NOTE: The above materials were cut at a water pressure of 55,000 psi [3800 kg/cm²].



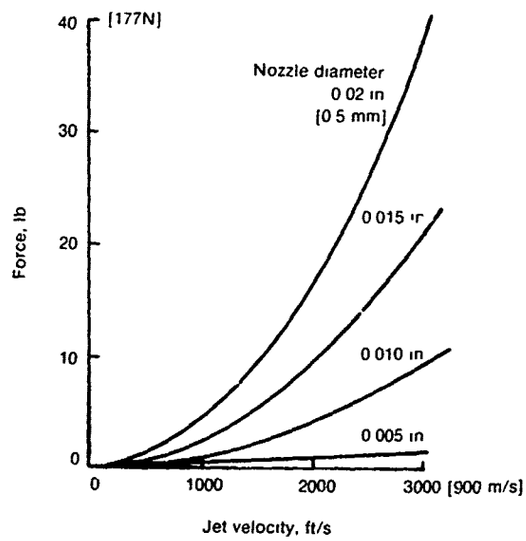
Jet velocity versus nozzle pressure



Nozzle flow versus jet velocity



Jet power versus nozzle flow



Force on workpiece versus jet velocity
(jet perpendicular to work)

Figure 10.3–4 Operating parameter relationships in HDM. (From K. F. Neusen, High velocity fluid jet cutting and slotting, Technical paper MR76-691, Society of Manufacturing Engineers, Dearborn, MI, 1976, pp. 8–10)

10.3 Hydrodynamic Machining—HDM

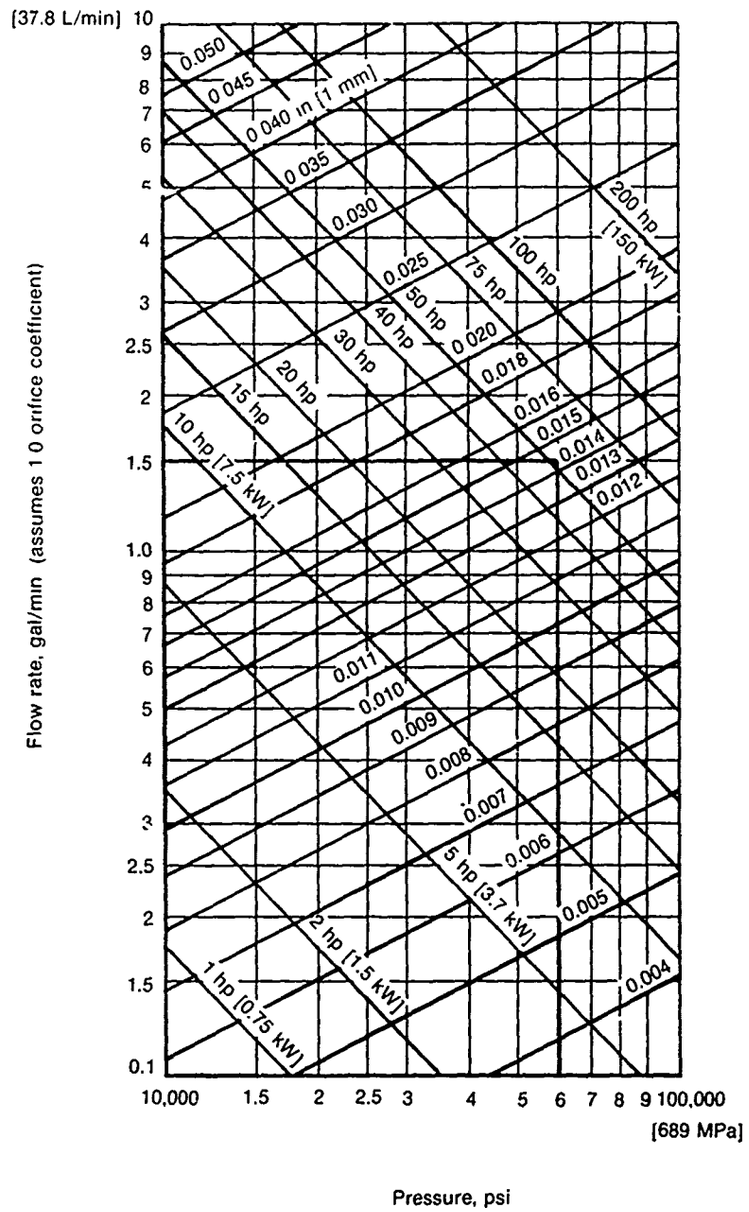


Figure 10.3-5 Pressure versus flow rate with various nozzle sizes. Knowledge of two variables enables determination of two other variables. For example: (Note heavy lines) if a cutting pressure to 60,000 psi is required, it can be obtained using a flow rate of approximately 1.5 gal/min with a 0.014-inch diameter stream. (Courtesy of Flow Equipment Company)

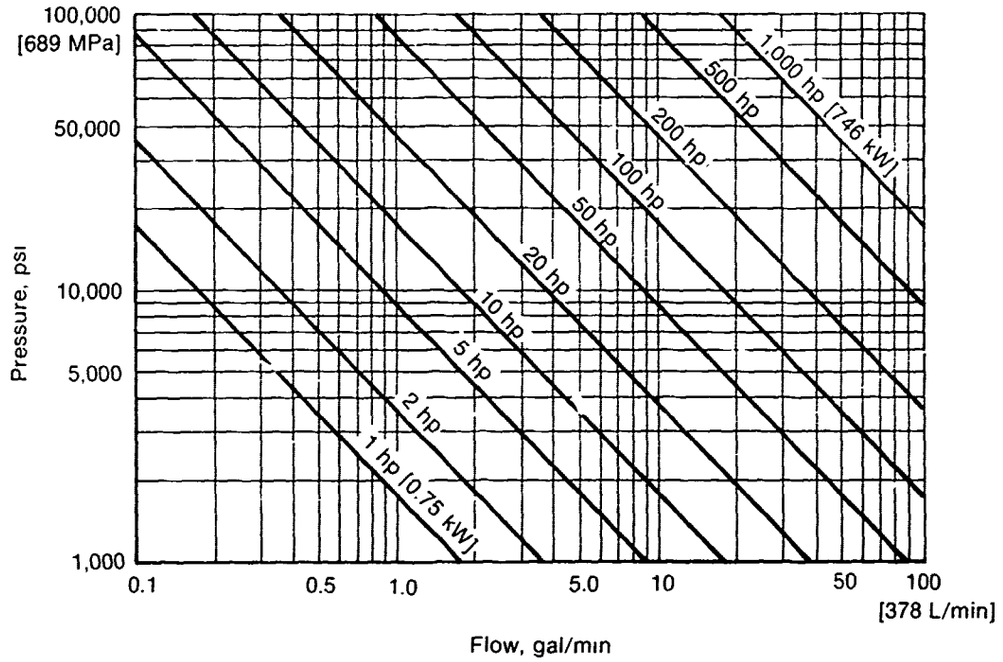


Figure 10.3–6 Hydraulic horsepower requirements of HDM for various pressures and flow rates. Example: 60,000-psi gallons at 0.7 gal/min requires 20 hp. (Courtesy of Flow Equipment Company)

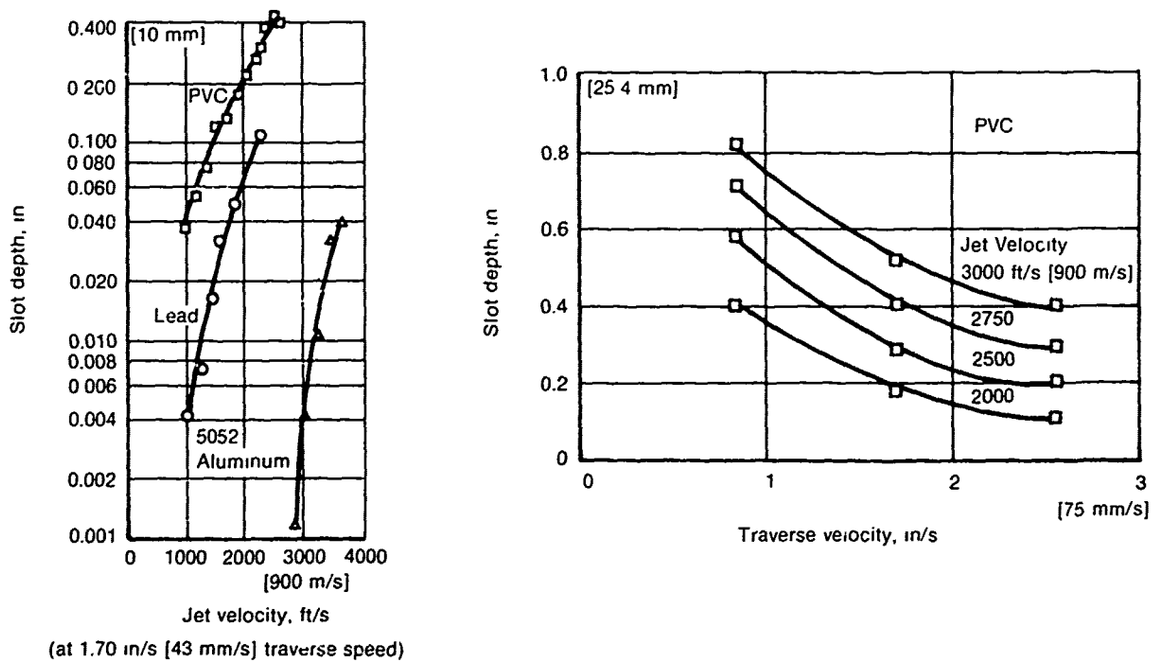
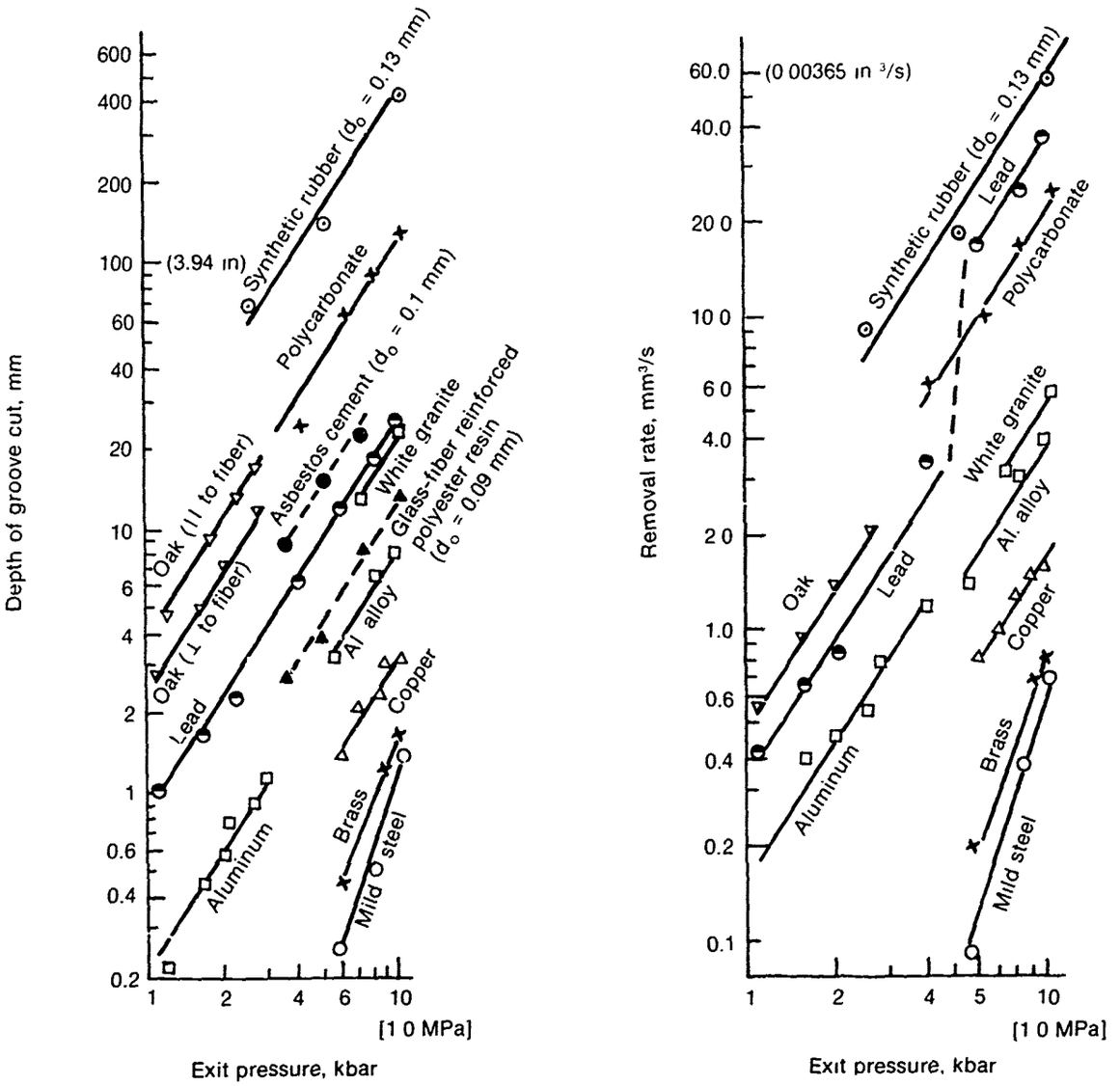


Figure 10.3–7 Slot depth for various materials (fixed nozzle 0.0094-inch diameter of 17-4 stainless steel, 60,000 psi pressure, plexol-201 fluid). (From K. F. Neusen, pp. 10–11)

10.3 Hydrodynamic Machining—HDM



Fluid: 1:1 mix H_20 and glycerine
Nozzle: Hardened steel, 0.15 mm (0.006 in) diameter
(unless d_o otherwise designated)
Standoff distance: 3 mm (0.12 in)
Angle: 90° to workpiece
Feed rate: 1.0 mm/s (0.039 in/s)

Figure 10.3-8 Depth of cut and material removal rate at different HDM pressures. (From O. Imanaka et al, Machining with continuous liquid jets at pressures up to 10 kbars, *Proceedings of the international conference on production engineering*, 1974 (Part I), p. 28. Japan Society of Precision Engineering, 1974)

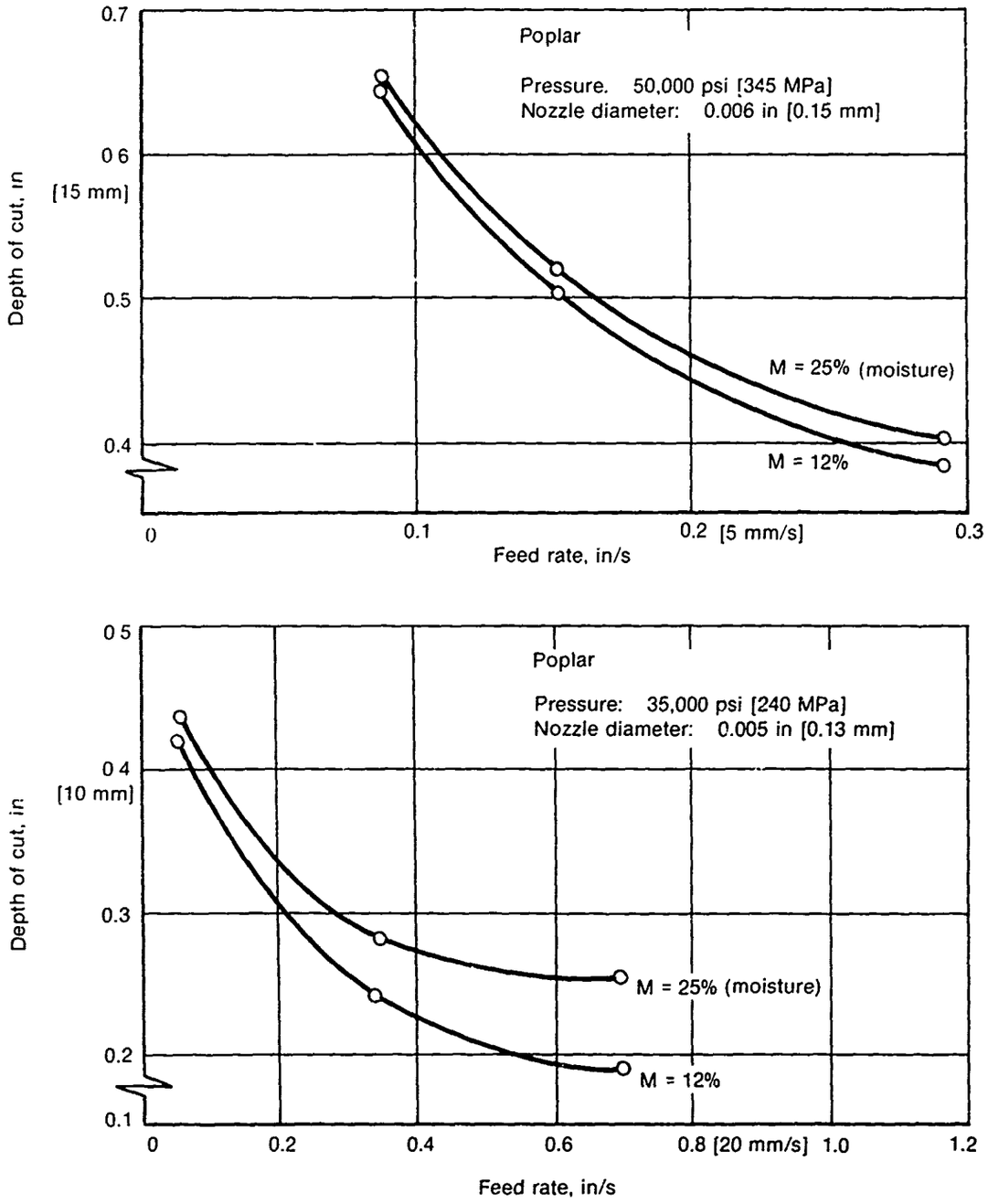


Figure 10.3–9 Feed rate and depth of cut for poplar at two levels of moisture content and two levels of HDM pressure (cut perpendicular to grain, 2 mm standoff distance, nozzle at 90°, fluid = H_2O). (M. P. dePlessis and M. Hashish, High energy water jet cutting equations for wood, Concordia, Univ., Montreal, Quebec, 1976)

10.3 Hydrodynamic Machining—HDM

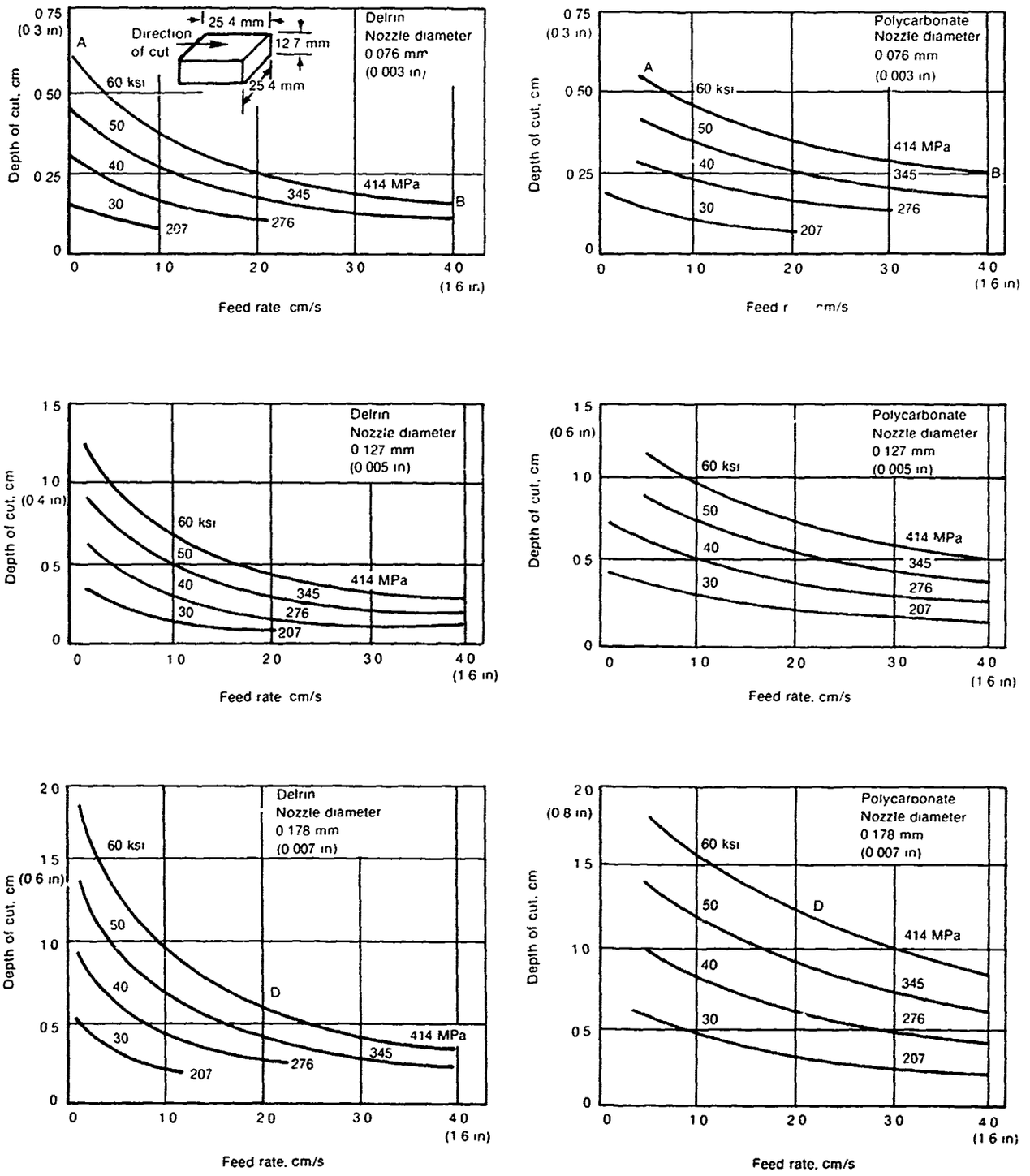


Figure 10.3–10 Depth of cut versus feed rate at various pressures. Delrin-Polycarbonate; saphire nozzle, 0.38 mm above surface; fluid = H_2O. (U. H. Mohaupt and D. J. Burns, Machining unreinforced polymers with high-velocity water jets, *Experimental Mechanics* 14 (April 1974): pp. 154–155)

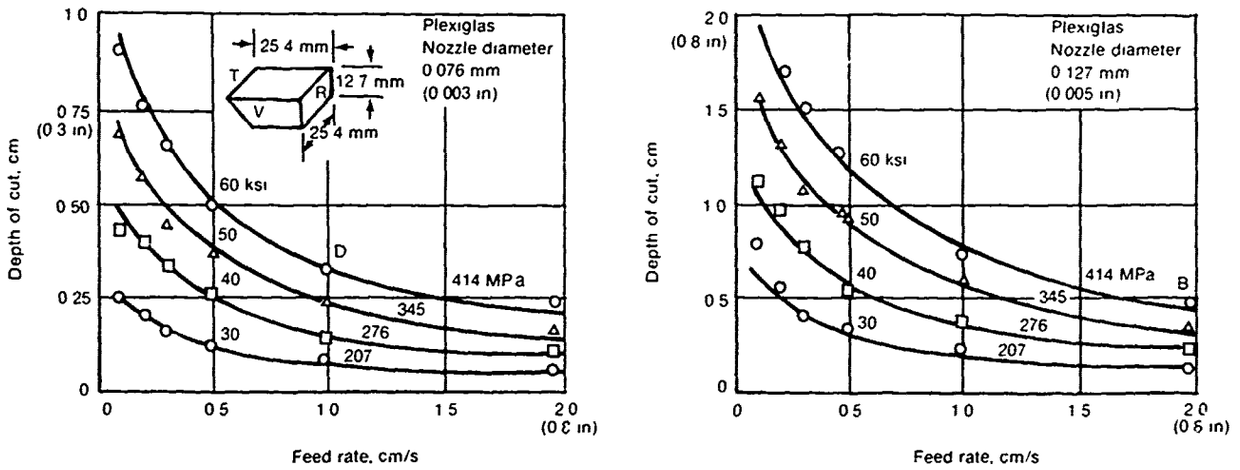


Figure 10.3–11 Depth of cut versus feed rate at various pressures. Plexiglas. (U H. Mohaupt and D. J Burns, p. 155)

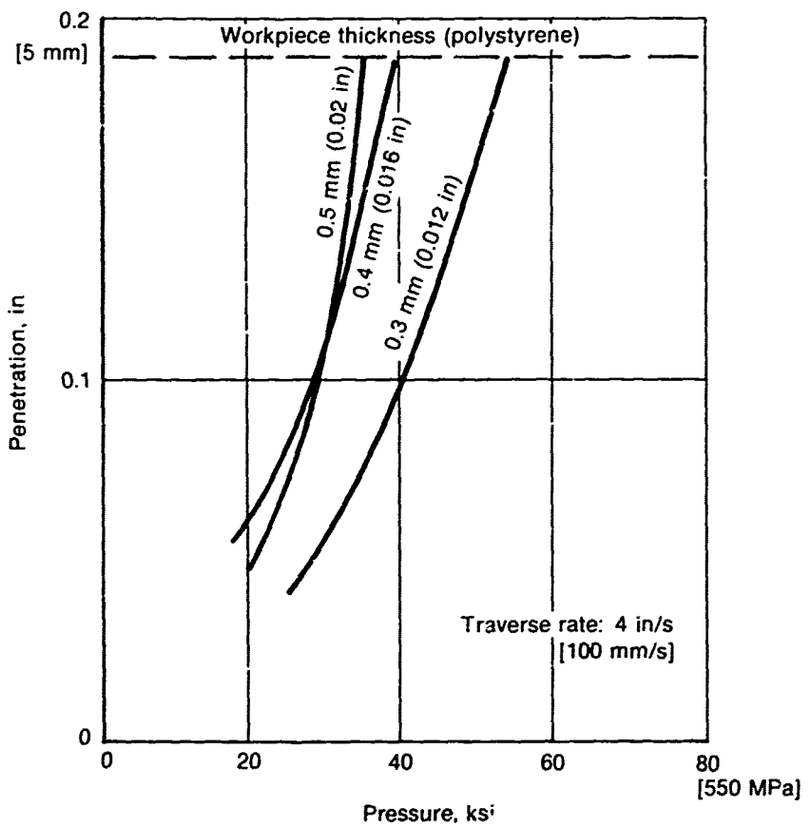


Figure 10.3–12 Effect of nozzle oriface diameter on workpiece penetration. (Courtesy of Grumman Aerospace Corporation)

10.3 Hydrodynamic Machining—HDM

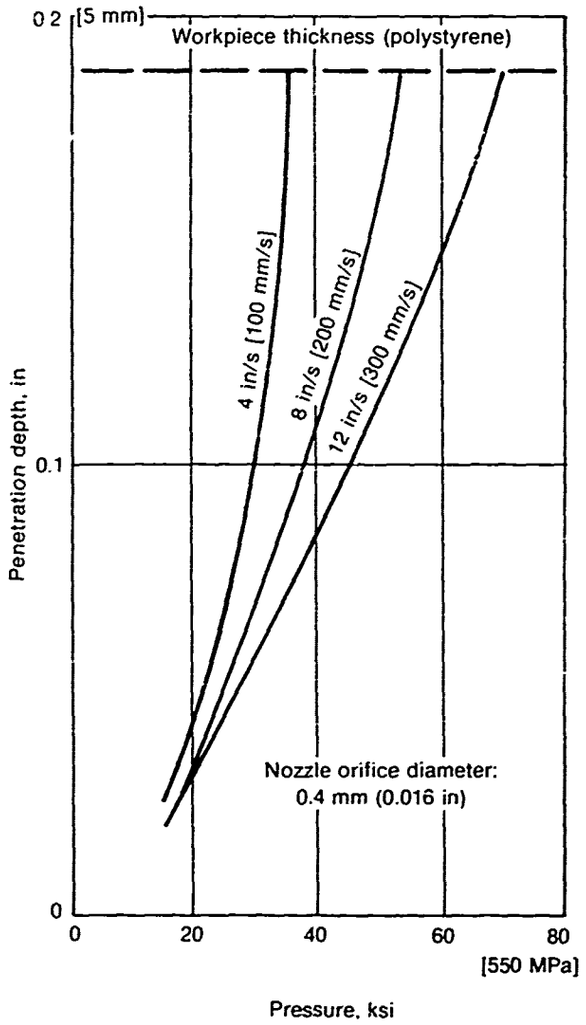


Figure 10.3–13 Effect of jet pressure on workpiece penetration. (Courtesy of Grumman Aerospace Corporation)

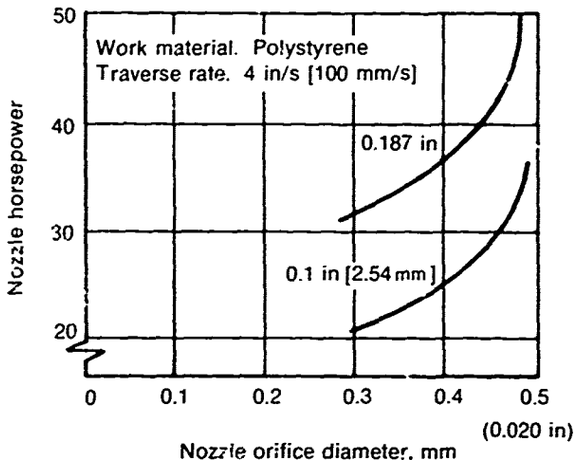


Figure 10.3–14 Nozzle horsepower versus nozzle diameter for plastic casing at 4 in/s traverse velocity for fixed penetration. (Courtesy of Grumman Aerospace Corporation)

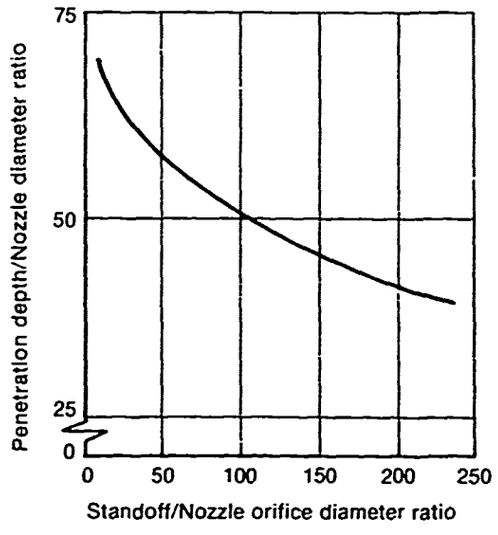


Figure 10.3–15 Effect of standoff distance on penetration depth. (Courtesy of Grumman Aerospace Corporation)

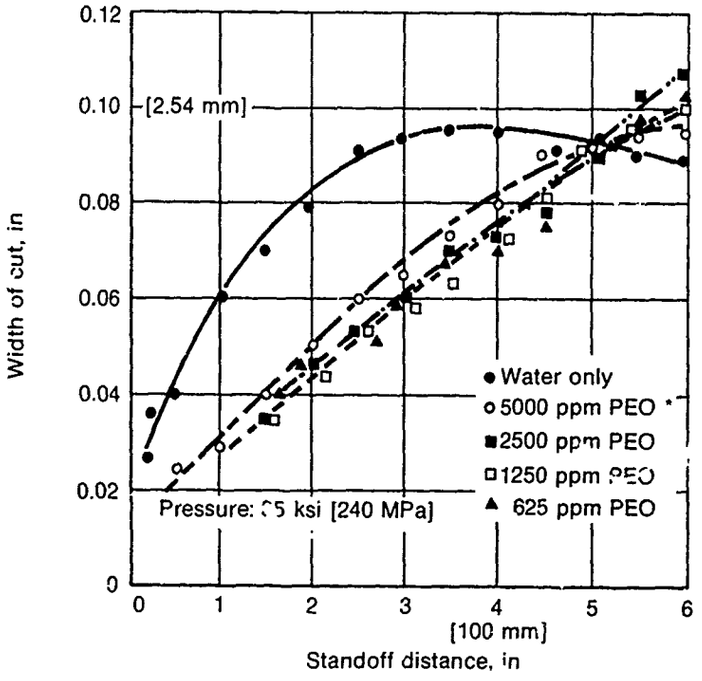


Figure 10.3–16 Width of cut versus standoff distance for aluminum. *PEO = Polyethylene oxide. (Courtesy of Grumman Aerospace Corporation)

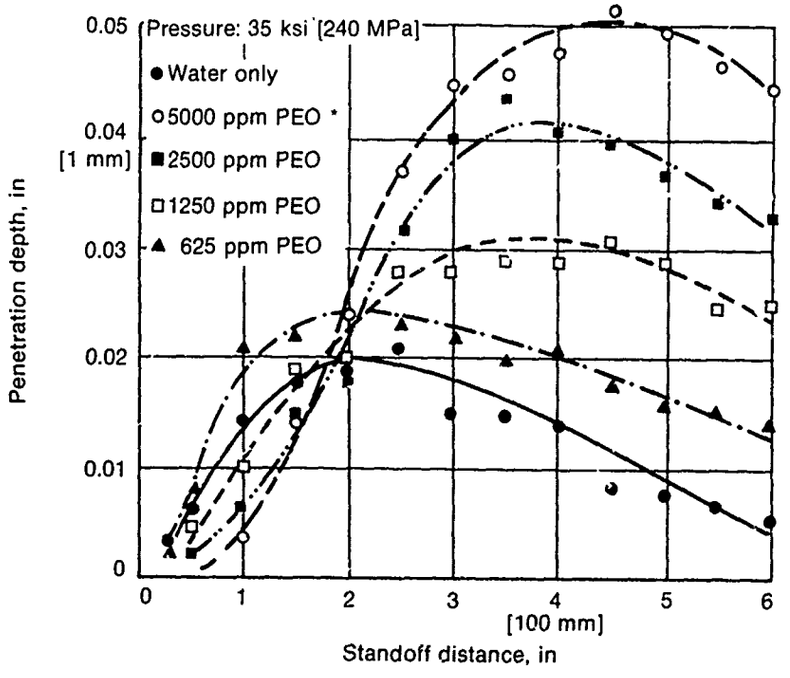


Figure 10.3–17 Penetration depth versus standoff distance for aluminum. *PEO = Polyethylene oxide. (Courtesy of Grumman Aerospace Corporation)

10.3 Hydrodynamic Machining--HDM

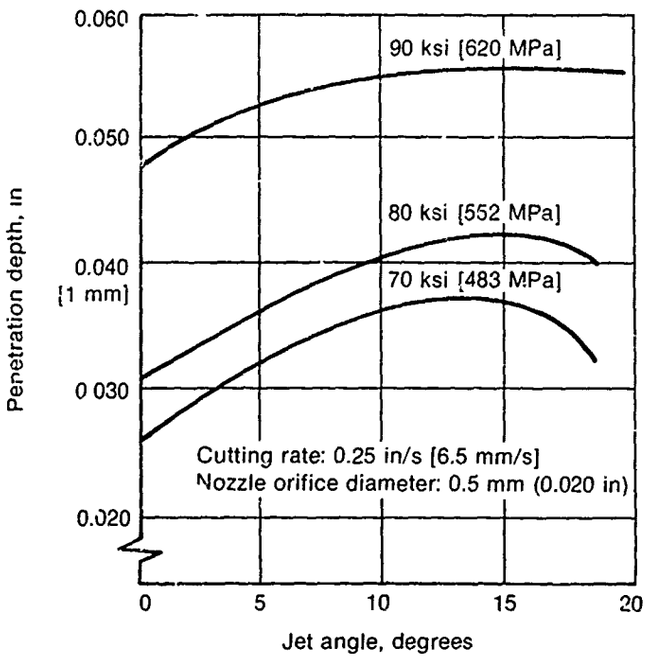


Figure 10.3-18 Effect of jet angle on penetration depth for steel cut under water. (Courtesy of Grumman Aerospace Corporation)

PROCESS SUMMARY

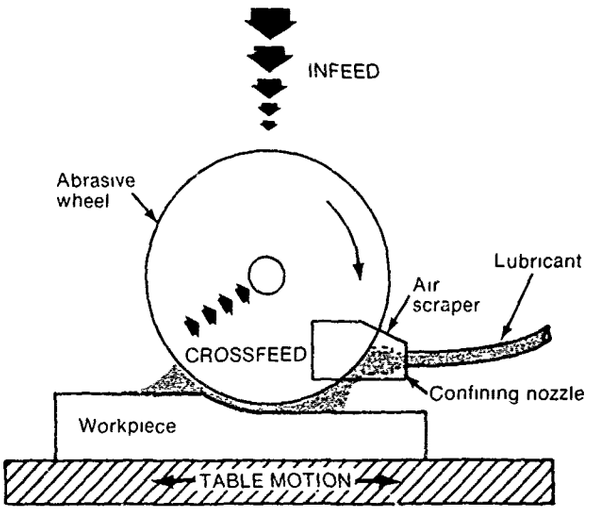


Figure 10.4-1 LSG schematic.

Principles

Low stress grinding (LSG) is an abrasive material removal process that leaves a low magnitude, generally compressive, residual stress in the surface of the workpiece Figure 10 4-1 shows a schematic of the LSG process. The thermal effects from conventional grinding can produce high tensile stress in the workpiece surface. By careful selection and control of the operating parameters, the thermal effects are minimized, thereby reducing the residual stresses, the attendant distortion and the possible reduction in high-cycle fatigue strength. The process parameter guidelines can be applied to any of the grinding modes surface, cylindrical, centerless, internal, etc. Additional description, details and data on LSG are provided in section 18.3, Surface Integrity, in the discussion of abrasive material removal processes.

Practical Applications

Grinding burn, distortion and cracking always have been associated with the improper use of abrasive processes, particularly when grinding high strength steels, high temperature alloys, titanium alloys and other sensitive alloys. Low stress grinding eliminates these effects by reducing the specific energy input. LSG should be used only on critical or highly stressed areas of a workpiece, such as those areas subjected to high cyclical stress or stress-corrosion environments. The enhanced surface integrity, minimal distortion and minimal residual stress in surfaces produced by LSG are important on highly loaded structural components As always, careful attention to the entire sequence of manufacturing processes is necessary to avoid reduction in the surface integrity produced in a component. Note that it is possible to reduce or eliminate the need for LSG by careful consideration of the total processing sequence and the proper placement of LSG within it

To maintain an acceptable level of productivity, LSG parameters should be applied only to the removal of the last few thousandths inch of material from the workpiece (see table 10.4-2) LSG should *not* be applied "all over" the workpiece. It should be considered for use only on critical areas, and then only if it is the final process affecting the "as shipped" surface. Note that heat treatment, shot peening or other post-grinding processing may affect the ground surface or may make LSG unnecessary

Productivity loss may also be relieved by an experimental investigation to determine what increase in the downfeed or infeed rates can be tolerated above those rates specified in table 10.4-2. Table 18 3-17 Grinding Parameters for IN-100 Turbine Blades (see section 18 3) provides data which show that no cracks were produced using a feed rate of 0.002 inch (0.05 mm) after certain low-stress-grinding parameters were adopted. Feed rates should not be increased, however, without doing the necessary experimental work for each particular alloy and situation. Generalizations about the grinding of sensitive alloys are dangerous.

Operating Parameters

TABLE 10.4-1 Typical Values for LSG Operating Parameters

(Parameters are listed in descending order of significance for low stress generation in the workpiece surface)

PROCESS PARAMETERS	GUIDELINES
1 Grinding wheel dressing technique	Frequent and coarse to maintain sharpness Maintain sharpness of dressing tool. Avoid dwell in using crush, roll, or single-point dressing tools
2 Wheel speed	Low, under 3,500 fpm [1,050 m/min].
3 Downfeed (or infeed) rate	0 0002 to 0.0005 inch/pass [0.005 to 0.013 mm/pass] with programmed reduction from conventional rates.
4 Grinding fluid	Oil-base fluid is preferred.
5. Wheel classification	Soft grade (G, H or I*). Open structure (6 or more). Grain size (60 or coarser)
6. Table (workpiece) speed	High, 50 fpm [15 m/min] and up Crossfeed is preferred to plunge motion.
7. Grinding fluid flow control	Adequate to high fluid flow. Assure placement of fluid between wheel and workpiece Flow controlling nozzle design. Reduce air film on wheel.

*Cylindrical grinding frequently requires use of harder wheels (with J grade prevalent), however, the other parameters must be selected to compensate for this extra hardness

10.4 Low Stress Grinding—LSG

Material Removal Rates and Tolerances

Material removal rates are low, but *good productivity can be attained* by successively reducing conventional material removal rates to LSG levels as the finished dimensions are approached Typical tolerances that can be obtained are in the ±0 0002 inch [±0.005 mm] range.

Surface Technology

Surface roughness values are typical of those attainable by fine grinding and range from 16 to 32 microinches R_a (0.4 to 0 8 μm). Plastically deformed debris, distortion and residual stress are minimal or absent The low residual-stress levels frequently are compressive, which further enhances the high-cycle-fatigue strength The absence of microcracks also contributes to high surface integrity A test specimen or check of the results from LSG is desirable. Either the distortion produced in a ground, thin test strip or a simple metallographic examination of the surface taken parallel to the lay can be a useful quality assurance test.

Equipment and Setup

Conventional grinding equipment can be used to produce LSG results. It may be necessary to modify the equipment to obtain the slower lower wheel speeds and higher table speeds The low infeed rates usually are attainable on a well maintained machine If it is not practical to modify some machine condition to secure the desired operating parameter, it still possible to attain LSG results. In this case all of the other parameters should be at their best levels to compensate for a deficiency in one of them.

Machining Characteristics

Results from LSG are typical of those attained by any fine *gentle* grinding operation Cleanliness of the lubricant, workpiece and machine are important, and it is most desirable to assure that a continuous, full stream of lubricant reaches the interface between the wheel and the workpiece. A closely fitted nozzle box is helpful.

SELECTED DATA

TABLE 10.4–2 Typical Infeed Schedule for Producing Surfaces by Low Stress Grinding

STEP	WORKPIECE STOCK REMOVAL*	INFEED RATE	
		inch/pass	mm/pass
Rough Grinding	From raw material dimension to within 0.010 inch [0.25 mm] of desired final dimension	up to 0.002†	up to 0.050†
Dress wheel			
Semi-finish Grinding	From 0.010 inch [0.25 mm] to 0.001 inch [0 025 mm] of final size	0 0003 to 0 0006	0.008 to 0.015
Dress wheel	Optional		
Finish Grinding (to low stress levels)	From 0 001 inch [0 025 mm] to final size	0.0001 to 0.0002	0.0025 to 0.005
	Optional: at final size, with continued application of grinding fluid	2 to 4 spark-out passes	

NOTE For additional data and description of low stress grinding, see abrasive machining discussion in section 18 3, Surface Integrity

*Data apply to the radius for cylindrical grinding and to the depth for surface grinding.

†This roughing rate should be such that roughness, tears, cracks, or microcracks in the surface are of lesser magnitude than the material remaining to be removed by the finishing and semi-finishing cuts.

PROCESS SUMMARY

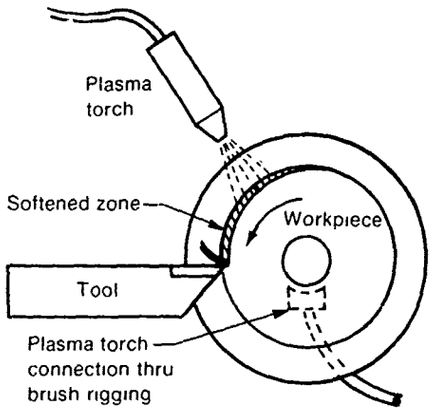


Figure 10.5–1 TAM schematic.

Principles

Thermally assisted machining (TAM) is the addition of significant amounts of heat to the workpiece immediately prior to single-point cutting so that the material is softened, but the strength of the tool bit is unimpaired (see figure 10.5-1). A steep temperature gradient is necessary, so the heat transfer properties of the work material are important High energy density in the heating source is a prime necessity Table 10.5-1 lists the energy densities for several heat sources While resistive heating and induction heating offer possibilities, the plasma arc offers the most practical and effective method for external heating at the required rates The plasma arc has a core temperature of 14500°F [8000°C] and a surface temperature of 6500°F [3600°C] The torch can produce 2000°F [1100°C] in the workpiece in approximately one quarter revolution of the workpiece between the point of application of the torch and the cutting tool This temperature will soften many high temperature alloys. The depth of heat penetration must be sufficient to secure material softening to the depth expected to be used by the cutting tool. Warm surfaces are not helpful—the temperature must reach the softening region for the work material. The residual temperature in the workpiece usually is only 100° to 200°F [35° to 100°C] Temperatures in thin wall sections may be higher.

TABLE 10.5–1 Energy Density of Heat Sources

HEAT SOURCE	DENSITY	
	W/in²	W/mm²
Electron beam	6 5 x 10⁹	1 x 10⁷
Laser beam	6 5 x 10⁹	1 x 10⁷
Plasma arc	6.5 x 10⁶	1 x 10⁴
Electric arc	6.5 x 10⁴	1 x 10²
Oxyacetylene torch	6.5 x 10³	10

Practical Applications

Hard-to-machine and high-temperature alloys are all candidates for "hot machining" or TAM Work materials with hardness ranges of 40 to 70 R_C should be considered for TAM. Poor thermal conductivity in the material can reduce the heat loss between the time of heat application and the time of cutting. Aluminum, copper, and titanium with their relatively high heat conductivities are not good candidate materials for TAM Most of the applications have been for turning; however, experimental work has involved milling and slotting. Cuts of long duration have the greatest potential for economic benefit from the addition of TAM.

Operating Parameters

The heat source (plasma torch) parameters are added to the conventional turning parameters. The standoff distance, angular position and shieldings for the torch are usually fixed by adapters to the machine tool. A careful balance between heat input, cutting depth and speed are needed to be sure that adequate, but not excessive, temperatures are achieved at the necessary depth in the workpiece surface at the instant of the cut.

Material Removal Rates and Tolerances

Conventional turning tolerances apply equally to thermally assisted machining, but material removal rates increase because the workpiece is softened. The shear forces are reduced; however, the depth of the softening zone governs the maximum depth of cut at which improved rates can be attained. Table 10.5-2 lists improved rates of cutting attained.

Surface Technology

When the heat input and cutting rates are properly balanced, the work material below the cut is usually not heated enough to alter the metallurgical structure. The surface roughness, plastic deformation, residual stresses, etc., associated with conventional turning apply equally to TAM.

10.5 Thermally Assisted Machining—TAM

TABLE 10.5-2 Comparison of Conventional Turning with TAM

MATERIAL	CONVENTIONAL TURNING		TAM	
	fpm	m/s	fpm	m/s
Nimonic 115	35	0.18	500	2.5
Austenitic chrome/manganese	10	0.05	500	2.5
Stellite, soft	20-50	0.10-0.25	400	2.0
Stellite, hard	grind only	grind only	350	1.8
Hard steel, 50 R_c	grind only	grind only	500	2.5
Inconel 718, STA	100	0.5	400	2.0
18% Mn steel	35	0.18	200	1.0
Waspaloy	90	0.45	400	2.0
Rene 41	28	0.14	415	2.1

Equipment and Tooling

Retrofitting adapters are available for applying plasma torch TAM to single-point, heavy-duty lathes. Capacities to 4 kW in heating are available. Shrouds or screens are desirable to contain the very hot chips. Standard tool bits are applicable; however, consideration should be given to using cutters with higher temperature capabilities, such as tungsten carbide, cermets, Borazon®-CBN or ceramics. The machine tool and fixtures should be rigid enough to accept the higher cutting speeds used.

Machining Characteristics

TAM has characteristics similar to conventional single-point cutting. A significant amount of noise may be produced by the plasma torch, so suitable muffling may be necessary. Protection from the chips is desirable because they may reach the 1000°F [550°C] temperature range. Eye protection from the arc is recommended.

Total Form Machining—TFM 10.6

PROCESS SUMMARY

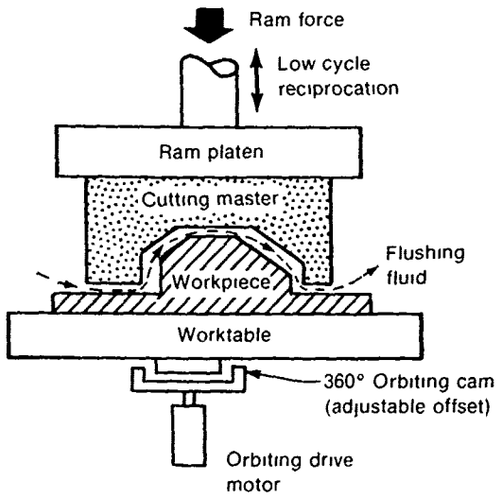


Figure 10.6-1 TFM schematic.

Principles

Total form machining (TFM) is a process in which an abrasive master abrades its full three-dimensional shape into the workpiece by the application of force while a full-circle, orbiting motion is applied to the workpiece via the worktable (see figure 10 6-1). The cutting master is advanced into the work until the desired depth of cut is achieved. Uniformity of cutting is promoted by the fluid which continuously transports the abraded particles out of the working gap. Adjustment of the orbiting cam drive controls the precision of the overcut from the cutting master. Cutting action takes place simultaneously over the full surface of abrasive contact

Practical Applications

Easily abradable, chalky, granular or friable materials are candidates for three-dimensional (or two-dimensional) forming or cavity-sinking operations by TFM. TFM can rapidly prepare graphite electrodes for EDM, and both the roughing and finishing electrodes can be made from the same master by adjusting the orbiting cam action. Redressing of worn electrodes can be accomplished in a few minutes. Using special fluids, TFM can polish surfaces produced by EDM Foundry cores can be generated with TFM

Operating Parameters

TABLE 10.6-1 Typical Values for TFM Operating Parameters

Abrasive master:	Steel die cavity with an untouched EDM surface or epoxy loaded with silicon carbide grit.
Grit size·	#180 to #20 (#100 provides a good balance between cutting rate and reasonable finish.)
Ram	
force:	Up to 1000 psi [6.9 MPa]. Normal operation is below 500 psi [3 5 MPa].
reciprocation	Once per second. ±0.10-inch [2.5 mm] amplitude.
Orbit offset:	0.020 to 0 180 inch [0.5 to 4 5 mm] is typical, up to 0 25 or 0.50 inch [6.5 or 12 5 mm] is available.
Fluid·	Filtered oil type comparable to EDM oils for machining graphite electrodes.

Material Removal Rates and Tolerances

Rates of material removal are determined by the ram force, the reciprocating offset and to some extent by the grit size and fluid flow rate. For three-dimensional forms, a comparison with profile milling of graphite shows an average saving in machining time of 90 percent with TFM. A 0.10-inch [2.5 mm] redressing of a graphite EDM electrode can be accomplished in 15 minutes with TFM. The sharpness of an inside corner is limited to the radius of the orbit setting. Outside corners can be as sharp as the master. Tolerances are only slightly greater than those of the master.

Surface Technology

The characteristics of the machined surfaces are related directly to the fineness of the abrasive grit used in the cutting master and to some degree to the extent of the orbiting offset. For graphite, the surface roughness produced is often sufficiently good so that the electrode can go to the EDM machine without any benchwork being necessary.

10.6 Total Form Machining—TFM

Equipment and Tooling

Equipment is regularly available in several sizes, with table sizes up to three feet (900 mm) square and up to 18 inches (460 mm) of ram travel. Orbiting offsets up to 0.50 inch (12.5 mm) are available. Filtered fluid systems accompany the machine or are built into the base.

The preparation of the abrasive cutting master, with appropriate overcut allowances, can start from a full-scale model and use a double-reverse, plastic-molding technique to secure the mirror image needed. Several other techniques for preparing the cutting master are available from the equipment builder.[1]

Machining Characteristics

The fluid flow in TFM eliminates the dust associated with conventional profile milling of graphite or other friable materials

[1]C. Krauter, 1976. EDM and TFM, The ideal marriage in a production die sinking center, Technical paper MR76-702, Society of Manufacturing Engineers, Dearborn, MI.

Ultrasonic Machining—USM 10.7
and Rotary Ultrasonic Machining—RUM

PROCESS SUMMARY

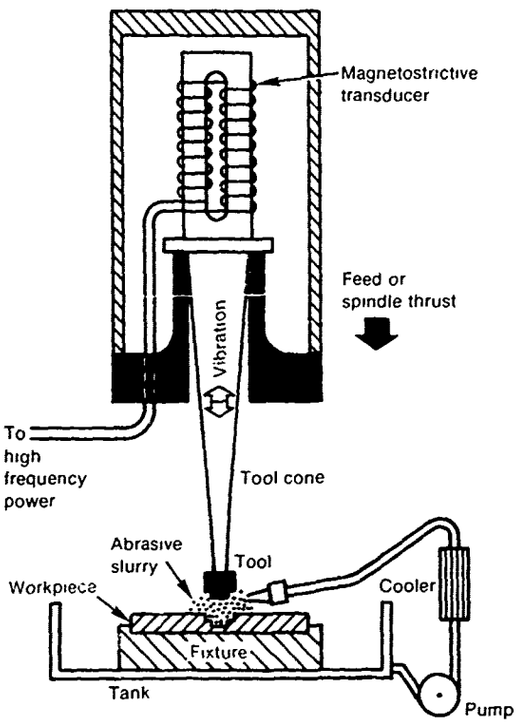


Figure 10.7–1 USM schematic.

Principles

Ultrasonic machining (USM) is the removal of material by the abrading action of a grit-loaded liquid slurry circulating between the workpiece and a tool vibrating perpendicular to the workface at a frequency above the audible range (see figure 10.7-1). A high-frequency power source activates a stack of magnetostrictive material, which produces a low amplitude vibration of the toolholder. This motion is transmitted under light pressure to the slurry which abrades the workpiece into a conjugate image of the tool form. A constant flow of slurry (usually cooled) is necessary to carry away the chips from the workface. The process is sometimes called ultrasonic abrasive machining (UAM) or impact machining.

A prime variation of USM is the addition of ultrasonic vibration to a rotating tool—usually a diamond-plated drill. Rotary ultrasonic machining (RUM) substantially increases the drilling efficiency. A piezoelectric device built into the rotating head provides the needed vibration. Milling-, drilling-, threading-, and grinding-type operations are performed with RUM (table 10.7-15 and figure 10.7-15).

Practical Applications

While USM can cut any material, conductive or nonconductive, metallic, ceramic or composite, it is most effective on materials harder than 40 R_C. Holes, slots and irregular shapes can be produced in delicate ceramics. Tool wear and taper in the cut can be limiting factors. A practical depth-to-width ratio is 2.5:1. Holes as small as 0.003-inch [0.076 mm] diameter have been made. Current practical limits are 3.5-inch [89 mm] diameter tools operating in 2.5-inch [64 mm] deep cavities. Trepanning is preferred to solid drilling. Threading of ceramics can be accomplished with a rotary tool or part. Slicing, coining, dicing, lapping, engraving, deburring, broaching, boring and trepanning operations are also practical. An ultrasonic assist is sometimes helpful in the performance of conventional drilling, grinding and drawing operations.

Operating Parameters

TABLE 10.7–1 Typical Values for USM Operating Parameters

Power.	200 to 4000 watts
Frequency.	10 to 40 kHz (most frequently 20 kHz)
Abrasive	
type:	Boron carbide (most frequently) (see tables 10.7–5 and 10.7–6)
size:	100 to 2000 (see table 10.7–10)
concentration.	20% to 60% by volume in water (use lower percentage for the larger tools). Oil is used sometimes for finishing
flow:	Ample, sharp and cool (replenish as becomes worn) (35° to 40°F [2° to 5°C] desirable)
Vibration amplitude:	0.0005 to 0.0025 inch [0.013 to 0.063 mm] (mean diameter of grit should be approximately equal to the vibration amplitude)
Tool tip force:	1 to 100 lb. [0.45 to 45 kg], generally less than 10 lb [4.5 kg])
Tool material:	Mild steel, 303 stainless steel, Monel, 5210C steel, molybdenum
Overcut and cutting gap:	Approximately 2 times grit size
Wear ratio:	0.7:1 to 1000.1 (see table 10.7–16)
Feed rate:	0.002 to 0.10 in/min [0.05 to 2.5 mm/min] (sensitive to debris accumulation in gap, to sharpness of grit and depth of cut)
Depth of cut:	Up to 2.5 inches [64 mm]
Area of cut:	Up to 3.5-inch [89 mm] diameter
Accuracy:	±0.001 inch [±0.025 mm] typical; ±0.0002 inch [±0.005 mm] possible
Taper:	Up to 0.005 inch/inch [0.005 mm/mm]
Surface roughness, R_a:	20 to 30 μin [0.51 to 0.76 μm]

10.7 Ultrasonic Machining—USM and Rotary Ultrasonic Machining—RUM

Material Removal Rates and Tolerances

Respectable machining rates combined with accuracy and good finishes can be achieved for very hard work materials. Vibration amplitude and frequency, area of cut, and static load are principal considerations; however, abrasive size and type, work material brittleness, and depth of cut are also important. The rate of penetration is inversely proportional to the area of the cut and proportional to the grit size and the square of the amplitude of vibration. Trepanning of cavities or holes is preferable to the use of solid tools. Cutting rates increase with the hardness of the abrasive grit. It is essential to maintain a good flow of fresh, sharp grit at the cutting interface and to flush this face free from chips and accumulations of debris. Excess static load can compact the grit and slow the penetration rate.

The delicate touch of USM, while slower in volume removal rate, can be especially valuable for reducing manufacturing losses of fragile workpieces. Breakout and chipping of exits of cuts can be a problem. Thin parts often are cemented to a sacrifice plate.

Accuracy is typically ±0.001 inch [±0.025 mm] and can achieve ±0.0002 inch [±0.005 mm] with special care. Typical operating conditions are listed in table 10.7-3. The rate of removal and other specific operating conditions are dependent upon the work material characteristics, as demonstrated in table 10.7-20.

Surface Technology

Surface roughness decreases and finish improves with smaller size grit and smaller vibration amplitudes or higher frequencies (see figures 10.7-3 to 10.7-5). USM typically achieves roughness values of 20 to 30 microinches R_a [0.51 to 0.76 μm]. Side walls of deep cavities can be rougher than the bottom face. There is no heat-affected zone, and there are no chemical or electrical alterations in the surfaces produced. The multitude of small impacts imparts a shallow, compressive residual stress to the surface. This residual stress promotes an increase in the high cycle fatigue strength of the work material after USM (see section 18.3, table 18.3-7). Side-wall channels can occur from the action of cavitation but will only be approximately the size of the abrasive grit.

Equipment and Tools

USM equipment for cavity sinking or piercing is available in a power range from 200 to 2400 watts and, with special engineering order, up to 4000 watts. The most common frequency is 20 kHz which can be adjusted about plus or minus 10 percent to attain better tuning for specific tooling. Special attachments or equipment adaptations provide ultrasonic assist for conventional drilling, grinding, forming and drawing. Tool material and grit are matched to the application, and for the best productivity, great care should be exercised in selecting and maintaining the amplitude of vibration. The tool should be designed to resonate at the desired frequency for best results, and it must be strong enough to resist fatigue failure. Tool materials are selected on the basis of ductility and toughness rather than hardness. The overcut between the tool form and workpiece shape is approximately equal to twice the size of the abrasive grit. Tool storage needs attention in order to reduce nicks and scratches that can cause early fatigue failure. Most forces are low, so workpiece clamping can be minimal. Fixturing should be positive so as to eliminate vibration of the workpiece. The slurry recirculation system should have cooling capability.

RUM equipment is available in a range of sizes and accessories as well as in portable units. Practical limit to tool weight is 1.4 oz [40 g]. The rotary heads provide capability for threading.

Machining Characteristics

There are no unusual safety considerations in USM, and the simplicity of the operation reduces the training or skill requirements. A good flow of slurry is desirable in order to maintain the cutting rate. Replenishment of the grit is needed at regular intervals. With water-based slurries, a rust-preventive treatment is desirable following the washout of the slurry. The proper choice of tool material and abrasive grit will result in satisfactory wear ratios between the workpiece and the tool. Taper in deep cuts can be relieved by the use of roughing and finishing tools. Because tool wear occurs mostly on the bottom face of the tool, profile precision is maintained.

SELECTED DATA

There are several valid techniques for selecting operating parameters for USM. The steps in table 10.7-2 are recommended as one logical sequence Supporting data come from the other figures and tables in accordance with the terms as explained in figure 10 7-2

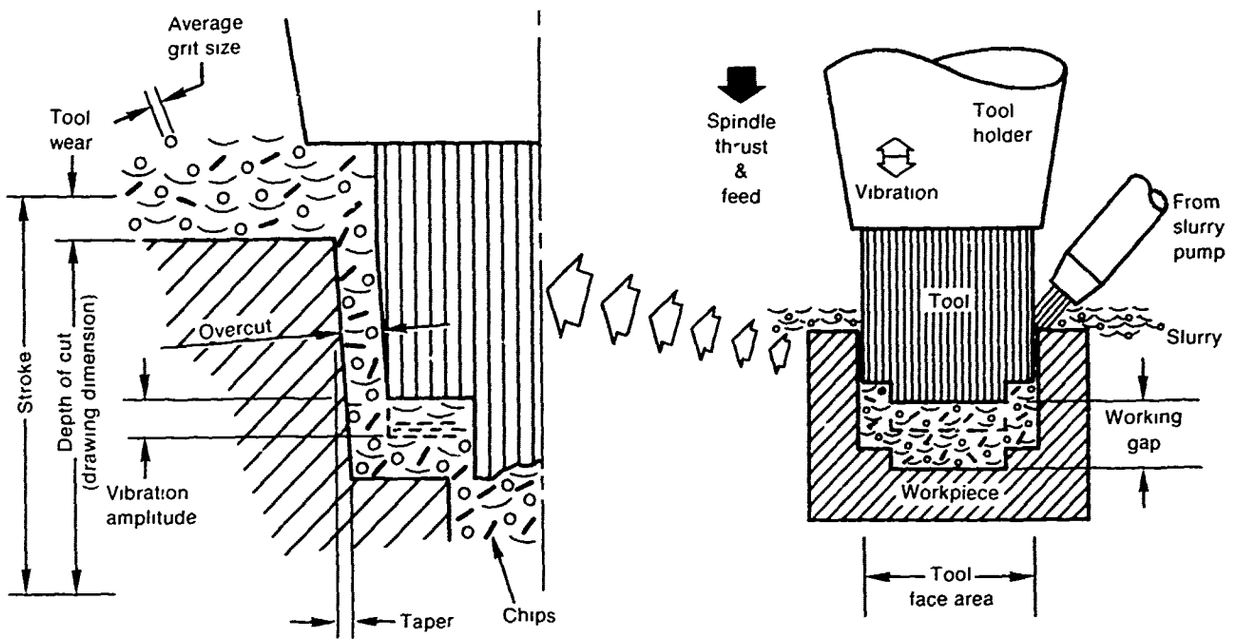


Figure 10.7-2 USM parameter terminology

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TABLE 10.7–2 Steps to Select USM Operating Parameters

ITEM	DATA
1. Workpiece material: type, hardness, metallurgical state	From engineering drawings or specifications Preferably hardness greater than 40 R_C. See table 10.7–4.
2. Configuration, finish and tolerance	From engineering drawing: Maximum contours depth-to-width = 2.5:1 Maximum dimension 4 inch [100 mm] Minimum width cut 0.003 inch [0.076 mm] Limited by tool type and shape. Consult machine vendors.
3. Area of cut	From engineering drawing: Calculate from part configuration. Minimize area by use of trepanning where possible.
4 Select type abrasive	Tables 10.7–5 to 10.7–10
5. Select abrasive grit size	Table 10 7–10; figures 10.7–3 to 10.7–5 Base on surface roughness and tolerance needs.
6. Select % concentration of slurry	Figure 10.7–6 Lower %'s for larger tool areas Water base generally; oil or alcohol sometimes used when water will dissolve workpiece.
7 Select tool material	Tables 10.7–11 and 10.7–12
8. Estimate: penetration rate vibration amplitude static load	Tables 10.7–13 to 10.7–15; figures 10.7–7 to 10.7–11
9. Select tool design	Allow overcut of 2 times grit size. Figure 10.7–12
10. Select equipment size	Table 10.7–19
11. Verify vibration frequency and amplitude. Refine other operating settings.	Trial cut and tuning of system. Establish wear rate.
12. Select depth of cut	Depth of cut or stroke equals drawing requirements plus tool wear allowance. Measure or estimate wear ratios Tables 10.7–16, 10.7–17 and 10.7–18; figures 10.7–13 and 10.7–14

TABLE 10.7–3 Typical USM Operating Conditions

PARAMETER	ROUGHING	SEMI-FINISHING	FINISHING
Tolerance, inch	±0.001	±0.0005	±0.00025
Roughness, microinch R_a	30	25	20
Grit size number	230	400	800
Grit average size, inch	0 00248	0 00090	0.00044
Grit average size, micron	63	23	11 2
Abrasive concentration, %	55	45	35
Overcut, inch	0.005	0.002	0.0005
Machine stroke	0.0025	0.0015	0.0005

TABLE 10.7–4 Materials That Have Been Successfully Machined Ultrasonically

Agate	Composites	Limestone	Silicon carbide
Alumina	Cold rolled steel	Lithium fluoride	Silicon nitrite
Aluminum oxide	Ebony	Micarta	Stainless steel—hardened
Barium titanate	Ferrite	Molybdenum	Steatite
Beryllium oxide	Formica	Molybdenum disilicate	Steel-hardened tools
Boron carbide (fused)	Garnet	Mother of pearl	Ti-6Al-4V
Boron composites	Germanium	Plaster of paris	Tungsten
Brass	Glass	Pyrolytic graphite	Tungsten carbide
Calcium	Glass-bonded mica	Quartz	Thorium oxide
Carbides	Graphite	Ruby	Uranium oxide
Carbon	Hardened 1095 steel	Sapphire	Uranium carbide
Ceramics	High pressure laminates	Silicon	Zirconium oxide

TABLE 10.7–5 Abrasives Used in USM

ABRASIVE	KNOOP HARDNESS	RELATIVE CUTTING POWER
Diamond	6500-7000	1.0
Cubic boron nitride (CBN)	4700	0.95
Boron carbide (B_4C)	2800	0.50-0.60
Silicon carbide (SiC)	2480-2500	0.25-0.45
Aluminum oxide (Al_2O_3)	2000-2100	0.14-0.16

TABLE 10.7–6 Selection of Abrasive

ABRASIVE	WORK MATERIAL
Boron carbide	Tungsten carbide, metals, high density ceramics, minerals, semi and precious stones.
Silicon carbide	Low density ceramics, glass silicon, germanium, mineral stones.
Aluminum oxide	Glass, low density, sintered or hard powder compounds.

SOURCE. G E Littleford, Machining by ultrasonics, 1971.

TABLE 10.7–7 USM Cutting Speed Index for Brittle Work Materials

(Soda glass, using 100 mesh B_4C abrasive = 100)

WORK MATERIAL	ABRASIVE			
	Boron Carbide			Silicon Carbide
	100 mesh	200 mesh	400 mesh	100 mesh
Soda glass	100	90	77	85
Hysil	73	66	54	
B9 borosilicate glass	86			
Ferroxcube IIIC	37			34
Ferroxdure (demagnetized)	(32)			
Quartz crystal	(57)			
Fused alumina	19			
Synthetic sapphire	19			
Synthetic ruby	18			
Flint stone	(72)			
Barium-titanate ceramic	110			109
Ceramic 507	(38)			35
Garnet	(58)			
Feldspar	(40)			
Spinel	(48)			
Slate	67			
Mycalex	(240)			(200)

SOURCE: E. A Neppiras and R. D. Foskett, Ultrasonic machining, *Philips Technical Review* 18 (1956–57), p 372.

NOTES: Tool used was mild steel, H-form, 1/2-inch [12 7 mm] square, limbs 1/16-inch [1.59 mm] thick, see figure 10.7–9.

Numbers in parentheses are estimates, interpolated from measurements under somewhat different conditions.

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TABLE 10.7–8 USM Cutting Speed Index for Metals
(Soda glass, using 100 mesh B_4C abrasive = 100)

WORK MATERIAL	ABRASIVE						
	Boron Carbide			Silicon Carbide	Alumina	Sand	Diamond Powder
	100 mesh	220 mesh	400 mesh	100 mesh	220 mesh	(grit size 0.012 in)	(grit size 0.001 in)
Soda glass	100	90	77	85	65	47	90
Brass (common yellow)	6.6	5.6					
Die steels							
K.E. 672 (approx AISI O1), R. 66	1.4	1.3					
C.S.K., R 62	3.9	3.6					
K.E. 672 (approx. AISI O1), R. 61	2.2	2.1		1.48	0.1	0.1	
K E. 672 (approx. AISI O1), R. 58		1.7					
Stainless steels							
18% Cr, 8% Ni, 0.1% C	2.1	1.9					
3 5% Cr, 8.4% W, 0.35% V, 0.3% C	1.2	1.1					
Carbon-chrome bearing steel (heat-treated)	1.4						
Sintered tungsten carbide, R. 76	4.1	3 5		2.55	0.2	0.2	4.3
Tungsten	4.8	4.3					
Stellite	4.0	3.7					
Germanium single crystal	(31)			(28)			
Titanium	(4.0)						
Beryllium	(7)						

SOURCE. E A Neppiras and R. D Foskett, p 371.
NOTE: Same tool used as in table 10.7–7. Numbers in parentheses are estimates interpolated from measurements under somewhat different conditions.

TABLE 10.7–9 USM Cutting Speed Index for Ceramic Work Materials
(Soda glass, using 100 mesh B_4C abrasive = 100)

WORK MATERIAL	ABRASIVE					
	Boron Carbide		Silicon Carbide			Alumina
	100 mesh	400 mesh	100 mesh	400 mesh	600 mesh	220 mesh
Chemical porcelain	70	14	53.5	11	2	25
Temperadex*	60	10	45	7.5	—	20
Feradex*	55	7	41	5	—	2
Vulcanex*	190	51	168	44	2	62
Z.Z. porcelain	90	32.5	75	26	2	10
H.T. porcelain	45	24	41	22	—	8
Frequentite*	47.5	27.5	45	26	—	20
Soda glass	100	45	80	37	6	70

SOURCE: E A Neppiras and R. D. Foskett, p. 371.
NOTE: Tool used was mild steel, circular, 1/4-inch [6.5 mm] diameter.
*Trade names of proprietary materials.

TABLE 10.7–10 Grit Sizes Used in USM

GRIT SIZE	PARTICLE SIZE	
	in	μm
Roughing		
120	0.0056	142
140	0.0048	122
170	0.0034	86
200	0.0026	66
230	0.00248	63
270	0.00175	44
325	0.00128	33
400	0.00090	23
Finishing		
500	0.00073	19
600	0.00057	14
800	0.00044	11
900	0.00038	10
1000	0.00032	8
1200	0.00022	6

NOTE. In estimating tool size with respect to tolerances required, the abrasive particle diameter can be considered as an overcut factor. For example, if a 1/4 inch [6.3 mm] diameter hole was being drilled with USM (using 180 grit), the diameter of the hole in the workpiece would be equal to 0 250 [6.350 mm] + 2 times 0.0034 [86 μm x 10^3] or approximately 0.257 inch [6.53 mm].

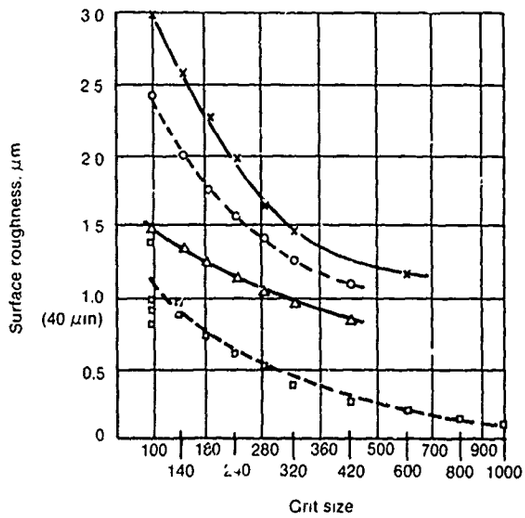


Figure 10.7–3 Surface roughness versus grit size of boron carbide abrasive. Work material key: x = glass; o = silicon-semi-conductor; Δ = mineralo-ceramic; □ = hard alloy steel. (D. C. Kennedy and R. J. Grieve, Ultrasonic machining—a review, *Production Engineer* 54 (1975), p. 485)

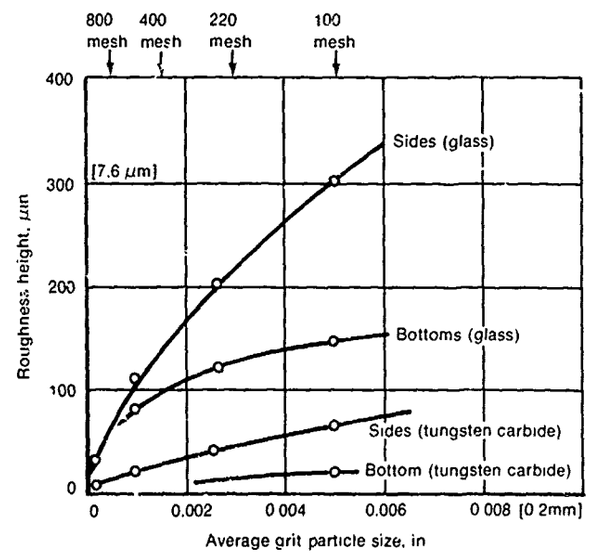


Figure 10.7–4 Roughness height versus grit particle size for holes in glass and tungsten carbide. (E. A. Neppiras and R. D. Foskett, p. 378)

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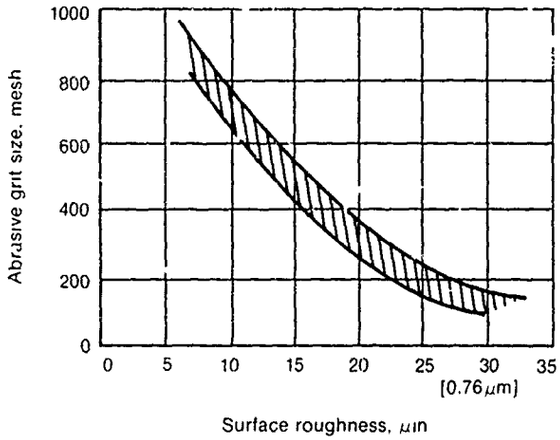


Figure 10.7–5 Grit size versus surface roughness. Smaller particles produce smoother finishes; larger particles cut faster. (Data modified from A. L. Roses, Techniques of ultrasonic machining, *Tool and Manufacturing Engineer* 46 (1969): 71–75)

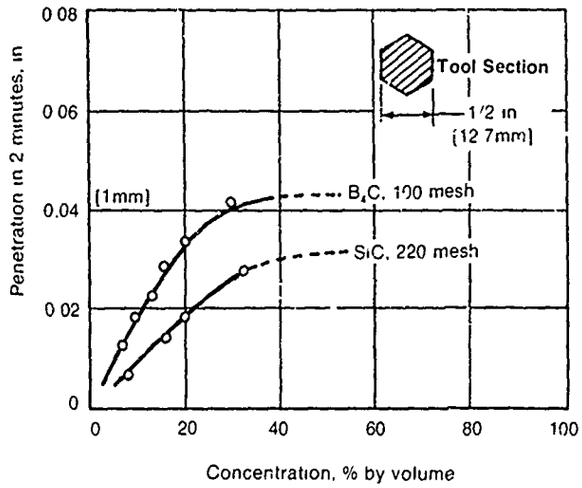


Figure 10.7–6 Penetration in glass as a function of slurry concentration. (E. A. Neppiras and R. D. Foskett, p. 373)

TABLE 10.7–11 Effect of Tool Material on Cutting Rate
(Soda glass work material; B_4C abrasive; optimum static load at 20 kHz)

TOOL MATERIAL	TOOL SHAPE	CUTTING RATE,* in/min			
		Amplitude = 0.002 in		Amplitude = 0.001 in	
		Abrasive 100 mesh	Abrasive 400 mesh	Abrasive 100 mesh	Abrasive 400 mesh
Copper	Circular, 1/2 in dia.	0.063	0.020	0.016	0.006
Brass (BSS 251)	Circular, 1/2 in dia	0.090	0.028	0.022	0.008
Mild steel (EN2)	Circular, 1/2 in dia.	0.086	0.022	0.021	0.007
Silver steel†	Circular, 1/2 in dia.	0.074	0.022	0.020	0.008
Stainless steel (18% Cr, 8% Ni, 0.1% C)	Circular, 1/2 in dia.	0.071	0.020	0.018	0.006
Tungsten carbide	Triangular, 1/8 in base	0.156	0.100	0.038	0.030
Mild steel (EN2)	Triangular 1/8 in base	0.150	0.102	0.036	0.029
Copper	Circular, 12.7-mm dia.				
Brass (BSS 251)	Circular, 12.7-mm dia.				
Mild steel (EN2)	Circular, 12.7-mm dia.				
Silver steel†	Circular, 12.7-mm dia.				
Stainless steel (18% Cr, 8% Ni, 0.1% C)	Circular, 12.7-mm dia.				
Tungsten carbide	Triangular, 3.2-mm base				
Mild steel (EN2)	Triangular, 3.2-mm base				

SOURCE: Adapted from E. A. Neppiras and R. D. Foskett, p. 370.

*Averaged over about 0.1 inch [2.5 mm] penetration.

†0.87% C, 0.020% S, 0.025% P, 0.28% Mn; tempered in air after oil-quenching from 800°C.

TABLE 10.7–12 Tool Wear for Various Tool Materi · · utting with 100 Mesh B_4C Abrasive
(Amplitude = 0.002 inch [0 051 mm]; optimum static load a· 20 kHz)

TOOL MATERIAL	TOOL SHAPE	TOOL WEAR*									
		Soda Glass Work Material					Tungsten Carbide Work Material				
		Longitudinal tool wear		Total penetration in workpiece		Tool wear as % of stock removal	Longitudinal tool wear		Total penetration in workpiece		Tool wear as % of stock removal
		in	mm	in	mm		in	mm	in	mm	
Copper	Circular, 1/2 in [12.7 mm] dia.	0.0025	0.063	0 520	13.2	0.48	—	—	—	—	—
Mild steel (EN2)	Circular, 1/2 in [12.7 mm] dia	0 018	0.46	1 850	42.0	1.0	0 110	2.79	0 125	3.18	88
Silver steel†	Circular, 1/2 in [12.7 mm] dia.	0.0026	0.063	0.546	13.9	0 46	0 012	0.30	0 046	1.17	26
Stainless steel (18% Cr, 8% Ni, 0.1% C)	Circular, 1/2 in [12.7 mm] dia.	0.008	0.20	1.150	29.2	0.7	0 016	0.41	0 045	1.14	35
Brass (BSS 251)	Circular, 1/2 in [12.7 mm] dia.	0.021	0.53	1 250	31.8	1.68	0 175	4.45	0 125	3.18	140
Sintered tungsten carbide	Triangular, 1/8 in [3 2 mm] base	0.0015	0.038	1.510	38.4	0.1	0 138	3.51	0 125	3.18	110
		Tool Steel					Tungsten Carbide				
Mild steel	Circular, hollow, int. dia. = 1/8 in [3.2 mm], ext. dia. = 1/4 in [6.4 mm]						0 156	3.96	0 125	3. 3	125
Mild steel	H-form, 1/2 in [12.7 mm] square, limbs, 1/16 in [1.6 mm] thick	0.053	1.35	0 024	0.6	220					
Mild steel	Circular, hollow, int. dia. = 0.33 in [8 4 mm], ext. dia. = 0.39 in [9.9 mm]						0.170	4.32	0.075	1.91	222
Brass	Extrusion shape T-form, height of T = 16 mm (0.63 in)						0 256 (avg)	6.5 (avg.)	0 125	3.18	205

SOURCE: Adapted from E. A. Neppiras and R. D. Foskett, p. 373.

*Average over 0.1 inch [2 5 mm] penetration.

†0.87% C, 0.020% S, 0.025% P, 0.28% Mn, tempered air after oil-quenching from 800°C

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TABLE 10.7–13 Material Removal Rates for Various Work Materials

WORK MATERIAL	MATERIAL REMOVAL RATE	
	in^3/min	mm^3/min
Carbon	0.015	246
Glass	0.016	262
Ceramics	0.005	82
Silicon	0 005	82
Germanium	0.006	98
Quartz (crystal)	0.007	115
Ferrite	0.014	230
Tungsten carbide	0.00025	4
Tool steel (hardened)	0.0002	3
Stainless steel (hardened)	0.0002	3
Boron carbide (fused)	0.00025	4
Pyrolytic graphite	0.010	16

TABLE 10.7–14 USM Material Removal Rate Index
(Cutting soda glass at 0.060 in/min [1.52 mm/min] = 100)

WORK MATERIAL	INDEX
Soda glass	100
Ceramic	70
Silicon	60
Tungsten carbide	4
Stainless steel	2

SOURCE G E Littleford, Machining by ultrasonics, 1971

TABLE 10.7–15 Rotary Ultrasonic Machining (RUM) with Rotating Diamond Impregnated Tool

WORK MATERIAL	DRILL DIAMETER		DEPTH OF CUT		MACHINING TIME	CONDITIONS
	in	mm	in	mm	seconds	
99.9 Alumina	0.042	1.07	0.250	6.35	130	20 kHz frequency 3000 rpm 120 grit core drill diamond tool 12 lb. [5.5 Kg] pressure
	0.125	3.18	0 250	6.35	20	
	0.250	6.35	0.250	6.35	25	
	0.375	9.53	0 250	6.35	30	
	0.500	12.70	0.250	6.35	38	
Glass	0.042	1.07	0.500	12.7	120	
	0.250	6.35	5.000	127	360	
Ferrite	0 080	2.03	0.250	6.35	70	
	0 125	3.18	0 250	6.35	30	
	0.250	6.35	0 250	6.35	35	
Boron composite	0.500	12.70	0.700	17.8	48	
	0.250	6.35	0.500	12.7	19	
	0 125	3.18	0.500	12.7	26	

SOURCE W R Tyrrell, A new method for machining hard and brittle materials, *SAMPE Quarterly* 1 (January 1970): 55-59

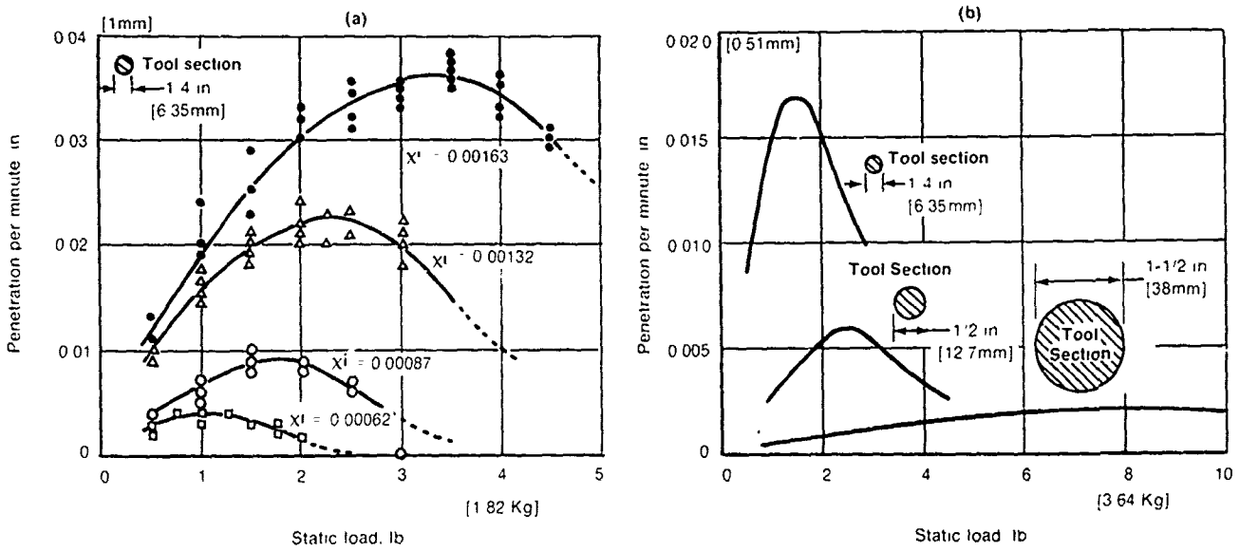


Figure 10.7–7 Penetration rate as a function of static load for (a) various amplitudes (ξ) and (b) various tool areas. (E. A. Neppiras and R. D. Foskett, p. 369)

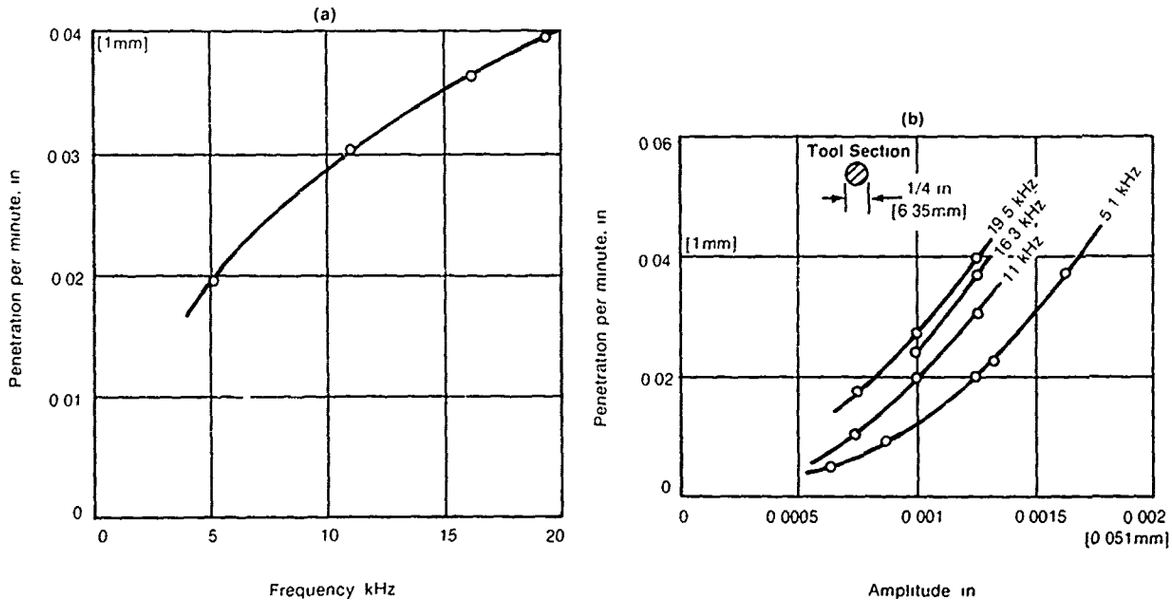


Figure 10.7–8 Penetration rates in glass as a function of (a) frequency, for a peak to peak amplitude of 0.00125 inch [0.038 mm] and constant static load; and (b) amplitude, for four operating frequencies and constant static load. (E. A Neppiras and R D Foskett, p. 369)

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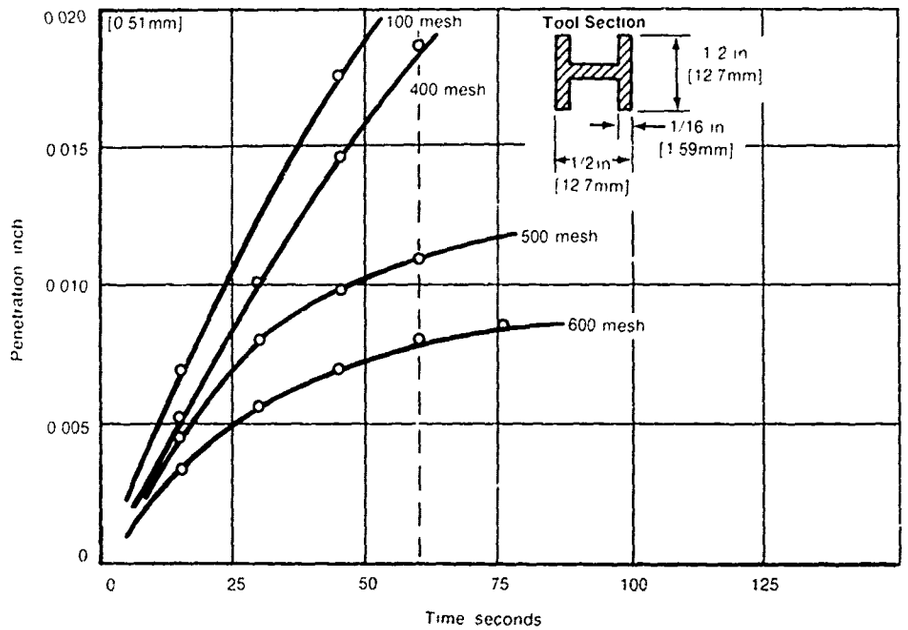


Figure 10.7-9 Penetration rate as a function of time for various grit sizes. Grit sizes given in British Standard Sieves (American Mesh sizes are essentially the same.) (E. A Neppiras and R D. Foskett, p. 370)

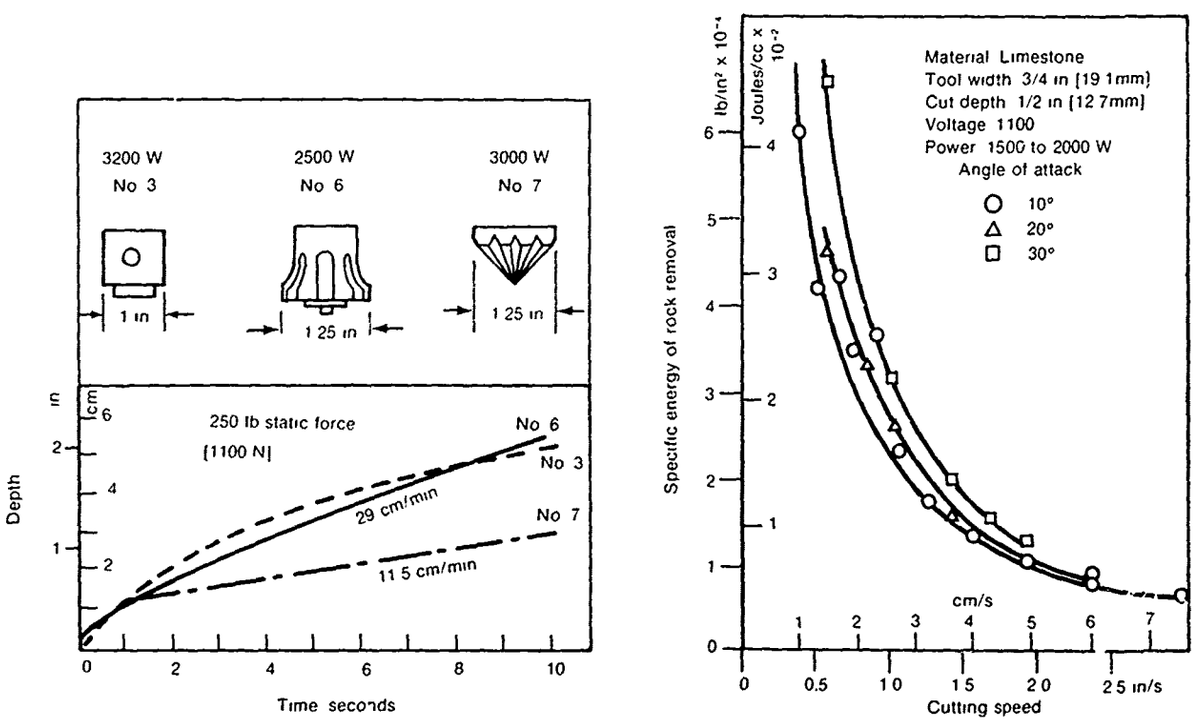
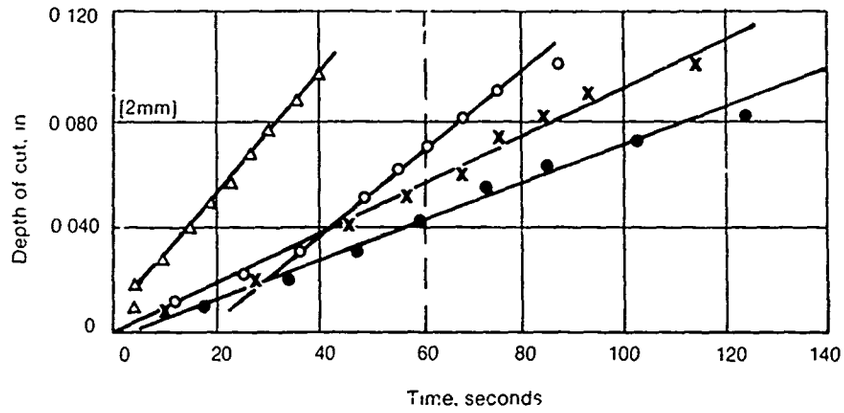
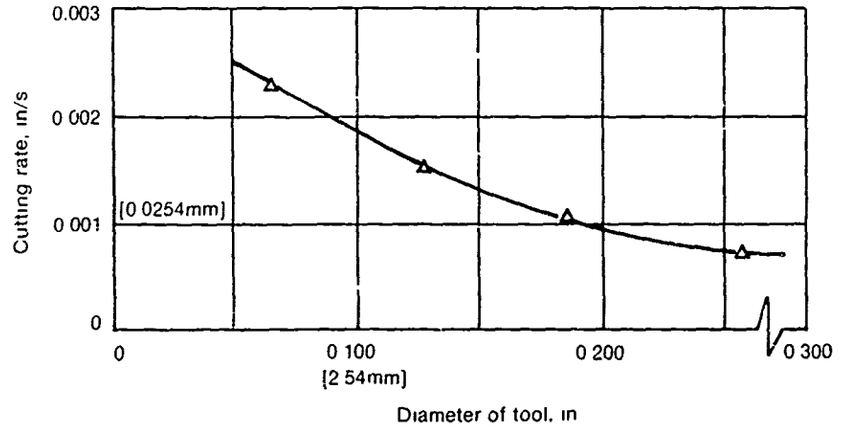


Figure 10.7-10 Drilling and layer removal rates for medium Indiana limestone processed with USM. *Left*, depth of drilling versus time for three types of tools operated at 10 kHz; *right*, specific energy at various cutting speeds and angles of attack at 10 kHz. (From K. F Graff, Application of sonic power to rock cutting, *Ultrasonics international 1973 conference proceedings*, pp. 31, 33)





KEY	DIAMETER OF TOOL		CUTTING RATE	
	in	mm	in/s	mm/s
△	0.0625	1.59	2.3	58
○	0.125	3.18	1 58	40
X	0.180	4.57	1 1	28
●	0.250	6.35	0 7	18

Figure 10.7-11 Cutting rates for stainless steel tools into ceramic work material. *Top*, determining rates for various size tools; *bottom*, rates as a function of tool diameter. (J Krawczyk, Ultrasonic grinding techniques in microminiaturization, Report No TR-958, Diamond Ordnance Fuze Laboratories, Washington, DC, 1961)

10.7 Ultrasonic Machining—USM
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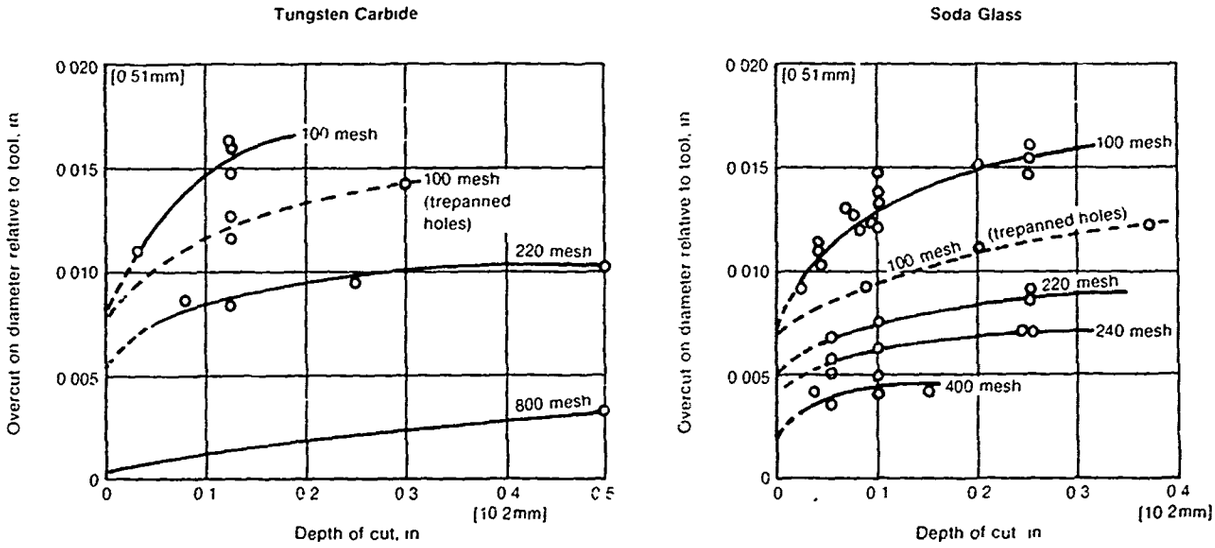


Figure 10.7–12 Overcut values for tungsten carbide and soda glass work materials cut with B^4C abrasive at various depths. (E. A. Neppiras and R. D. Foskett, p. 374)

TABLE 10.7–16 General Wear Ratios

TOOL MATERIAL	APPROXIMATE WEAR RATIO (ratio of depth of cut to loss of tool size)			
	Workpiece Materials			
	Glass	Steatite	Tungsten carbide	Ceramic
Brass	40-50	10	0.7	40
Annealed low C steel	100		1.1	75
Cold rolled steel	100	35	3 9	75
Stainless steel	150	40	2 8	100
Tungsten carbide	1000		0.9	

SOURCE. J. Krawczyk, Report No. TR-958, Diamond Ordnance Fuze Laboratories, 1961

NOTE· General cutting conditions 1/4-inch diameter mild steel tool; 20 kHz, 320 grit B_4C; 1-1/2 lb pressure.

TABLE 10.7–17 Representative USM Penetrating and Tool Wear Rates at 700 Watts Input

MATERIAL	RATIO STOCK REMOVED TO TOOL WEAR	MAXIMUM PRACTICAL MACHINING AREA		AVERAGE PENETRATING RATE*	
		in²	cm²	in/min	mm/min
Glass	100.1	4.0	25.8	0.150	3.81
Ceramic	75:1	3.0	19.4	0.060	1.52
Germanium	100.1	3.5	22.6	0 085	2.16
Tungsten carbide	1.5:1	1.2	7.7	0 010	0.25
Tool steel	1:1	0.875	5.6	0.005	0.13
Mother of pearl	100:1	4.0	25.8	0.150	3.81
Synthetic ruby	2:1	0.875	5.6	0.020	0.51
Carbon-graphite	100:1	3.0	19.4	0.080	2.00
Ferrite	100:1	3 5	22.6	0.125	3.18
Quartz	50:1	3.0	19.4	0 065	1.65
Boron carbide	2:1	0 875	5.6	0.008	0.20
Glass-bonded mica	100:1	3.5	22.6	0.125	3.18

SOURCE. Data from Raytheon Company, Impact grinders for ultrasonic machining, 1961

NOTE. Tool material was cold rolled steel in all cases. = 320 mesh Boron Carbide was used in all cases

*1/2-inch [12 7 mm] diameter tool, 1/2-inch [12 7 mm] deep

TABLE 10.7–18 Representative USM Penetrating and Tool Wear Rates at 100 Watts Input

MATERIAL	SOLID TOOL DIAMETER		FORCE		BEST CUTTING RATE		ABRASIVE/ WATER RATIO BY VOLUME	STOCK REMOVAL RATIO WORKPIECE (vs) TOOL
	in	mm	lb	kg	in/min	mm/min		
Glass	0.25	6.35	1	0.45	0.075	1.91	1.4:1	100:1
Aluminum oxide	0.25	6.35	5	2.27	0.010	0.25	1.4:1	13:1
Tungsten carbide	0 25	6.35	1	0.45	0.002	0.05	1.4:1	1:1
Carbon	0.25	6.35	0.5	0.27	0.100	2.50	1.4.1	100:1
Steatite	0 25	6.35	1	0.45	0.090	2.29	1.4:1	200:1
Germanium	0.25	6.35	1	0.45	0.110	2.79	1.4:1	100:1
Silicon	0.25	6.35	1	0.45	0.110	2.79	1.4:1	100:1
Quartz	0.25	6.35	3	1.36	0.070	1.79	1 4:1	50:1
Glass	0.125	3.18	1	0.45	0.125	3.18	1.4:1	100:1
Aluminum oxide	0.125	3.18	1	0.45	0 030	0.76	0.25:1	10:1
Carbon	0.125	3.18	0.5	0.27	0.250	6.35	0.25:1	100:1
Germanium	0.125	3.18	1	0.45	0.125	3.18	0.25:1	100:1
Silicon	0.125	3.18	1	0.45	0.125	3.18	0.25:1	100:1
Tungsten carbide	0.125	3.18	1	0.45	0.004	0.10	0.25:1	1:1

SOURCE: Data from Raytheon Company, Impact grinders for ultrasonic machining, 1961.

NOTE: Tool material was cold rolled steel in all cases; = 320 mesh Boron Carbide was used in all cases

10.7 Ultrasonic Machining—USM
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TABLE 10.7–19 Equipment Size
(Estimate of watts required for 20 kHz equipment using 120 mesh B_4C abrasive and optimum parameters)

CUTTING RATE						WATTS
Glass		Hard Alloy		Germanium		
$in^3/min \times 10^{-4}$	mm^3/min	$in^3/min \times 10^{-4}$	mm^3/min	$in^3/min \times 10^{-4}$	mm^3/min	
92	150	3.1	5	31	50	250
214	350	4.9	8	61	100	500-600
490	800	12 2	20	122	200	1000
900	1500	18 3	30	183	300	1500
1800	3000	45.8	75	427	700	4000

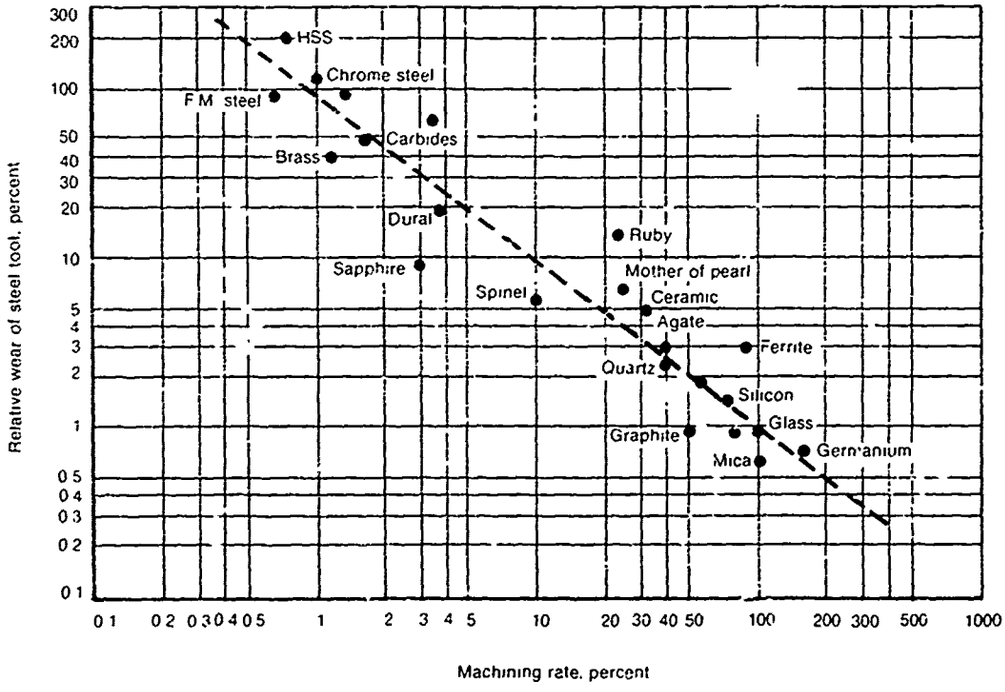


Figure 10.7–13 Tool wear versus machining rate. Relative wear rate of steel tool in various work materials. 100% is 5 mm/min (0.20 in/min) in glass. (M. Aqithan and V. C. Venkatesh, Tool wear phenomenon in ultrasonic drilling, *Proceedings of 5th all India machine tool design and research conference*, University of Roorkee, 1972, p. 625)

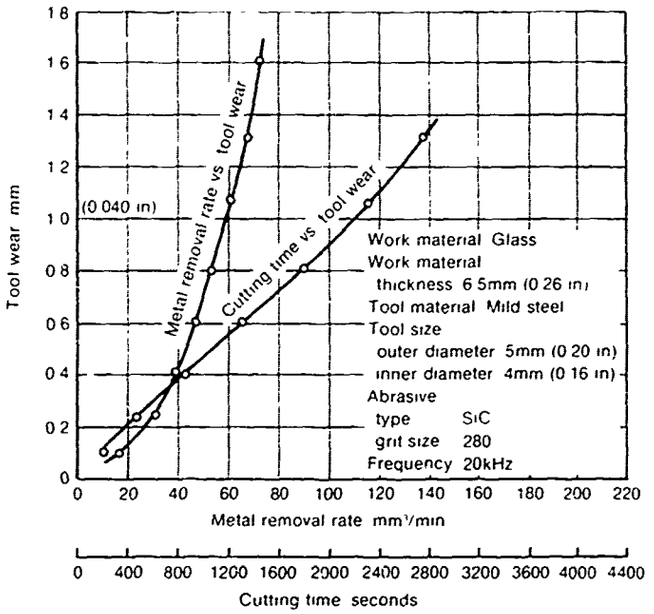


Figure 10.7-14 Tool wear versus machining rate and cutting time. (M. Adithan and V C Venkatesh, p 627)

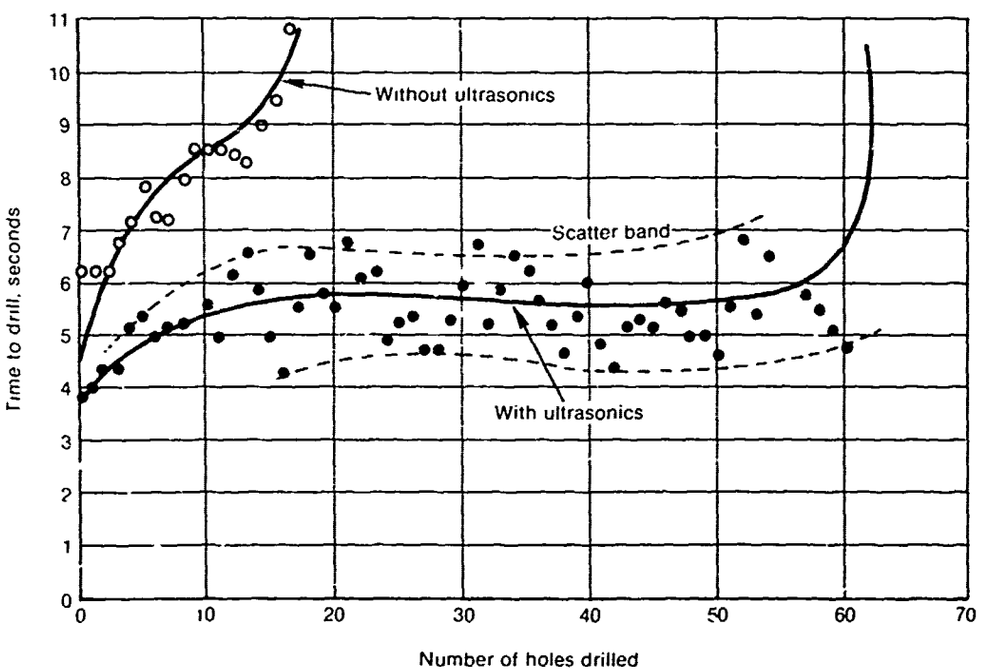


Figure 10.7-15 Improvements in drilling time and number of holes drilled using rotary ultrasonic machining. Test drilling of 1/16-inch [1.59 mm] Ti-6Al-4V with #30 cobalt twist drill at 1390 rpm and 54 lb [24.5 kg] force in a Branson UMT3. (W Tyrrell, Rotary ultrasonic machining. Technical paper MR70-516, Society of Manufacturing Engineers. Dearborn, MI, 1970)

10.7 Ultrasonic Machining—USM
and Rotary Ultrasonic Machining—RUM

TABLE 10.7–20 General Recommendations of Conservative Starting Conditions for USM

PARAMETER	WORK MATERIAL							
	Glass		Ceramics		Hard Metals (40-60 R_c)	Composites (e.g., glass epoxy)	Tungsten Carbide	Stone
	Roughing	Finishing	Large area	Small area				
Tool material	mild steel	mild steel	stainless steel	stainless steel	tool steel	mild steel	mild steel	tool steel
Abrasive								
Type	B_4C	B_4C	B_4C	B_4C	SiC	B_4C	B_4C	Al_2O_3
Size	320	500	320	180	240	320	240	180
Percent concentration	20	60	20	40	50	40	50	20
Carrier fluid	H_2O	light oil	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O
Power								
Frequency, kHz	20	20	20	20	20	20	20	10
Watts	700	100	400	200	500	300	500	1000
Amplitude,								
in	0.002	0.001	0.002	0.001	0 0005	0.0015	0.0005	0 004
[mm]	[0.051]	[0.025]	[0.051]	[0 025]	[0 013]	[0.038]	[0.013]	[0.102]
Spindle thrust, lb	5	2	2	1	4	2	4	10
[kg]	[2.27]	[0 91]	[0 91]	[0.45]	[1 82]	[0 91]	[1.82]	[4.54]
Material removal								
Rate,								
in^3/min	0 030	0.015	0.004	0 005	0 0002	0.016	0.0003	0.15
$[mm^3/min]$	[491]	[246]	[65.5]	[81 9]	[32.7]	[262]	[4.9]	[2458]
Penetration,								
in/min	0 150	0.075	0.020	0.025	0 001	0.080	0.0015	0.150
[mm/min]	[3 81]	[1.90]	[0 51]	[0 64]	[0 025]	[2.0]	[0.038]	[3.81]
Relative percent*	100	50	15	20	6	50	4	500
Depth of cut, in	0.5	0.5	0.1	0 1	0.25	0.1	0 1	1 0
[mm]	[12.7]	[12.7]	[2.5]	[2 5]	[6 4]	[2 5]	[2.5]	[25.4]
Cutting time, minutes	3 4	6.8	5.0	4.0	250.0	12.5	66 0	6 6
Wear ratio (work to tool)	100	200	75	75	75	100	2	150
Tolerance, ± in	0.0010	0.0005	0.0010	0 0010	0.0015	0.0010	0.0005	0.0020
[± mm]	[0 025]	[0.013]	[0.025]	[0.025]	[0.038]	[0.025]	[0.013]	[0.051]
Surface roughness, R_a,								
μin	40-60	20-40	40-60	40-60	10-20	40-60	10-20	60-80
[...]	[1-1.5]	[0 5-1]	[1-1.5]	[1-1.5]	[0.25-0.5]	[1-1.5]	[0.25-0.5]	[1.5-2]

NOTE. Based generally on a tool face area of 0.2 in^2 [1 29 cm^2]

*Based on soda glass as 100%

SPECIFIC APPLICATIONS DATA

TABLE 10.7–21 Specific Applications Data for Ultrasonic Machining

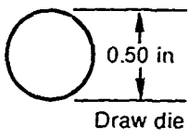
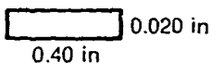
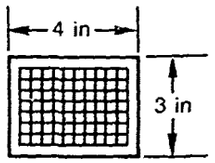
Work material:	Tungsten Carbide		Phenolic Molding	Carbon
Workpiece configuration:				
Abrasive type:	B_4C	B_4C	Al_2O_3	SiC
grit size:	320	600		400
percent concentration:				50
Power supply frequency, kHz:	20	20	20	20
power, W:				600
amplitude, in:				0.0015
Spindle thrust, lb:				Controlled feed rate
Depth cut, in:	0.187	0.187	0.190	0.040
Cutting time, min.	15	10	2	10
Wear ratio (work to tool):				0
Tolerance, in:		±0 0002	±0.001 for size, ±0.0025 for depth	±0.0005
Surface roughness, μin R_a:	22	15		16
Remarks:	Roughing cut, trepanned, 7/16-inch ID. Through hole.	Finishing cut, 0.4992-inch OD tool size. Through hole.	Bottom hole.	Very delicate part.

TABLE 10.7-21—Continued

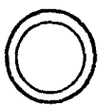
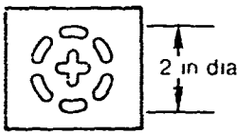
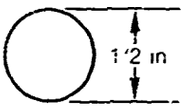
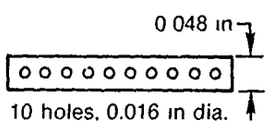
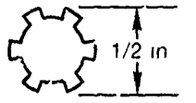
Work material	Silicon Nitrite	Glass-Graphite Epoxy Composite	Glass
Workpiece configuration	 1.0 in OD 0.9 in ID Rings — trepanned from block	 2 in dia 23, slots 0.025 x 0.060 in to 0.025 x 0.375 in	 1/2 in
Abrasive type.	B_4C	B_4C	B_4C
grit size.	240	280	200
percent concentration	50	40	35
Power supply frequency, kHz	20	20	25
power, W	600	300	
amplitude, in	0.002	0.0011	0.0015
Spindle thrust, lb:	1.5	4	
Depth cut, in	0.30	0.060	0.150
Cutting time, min	12	2	1
Wear ratio (work to tool)	10:1	80:1	100:1
Tolerance, in	± 0.001	± 0.001	
Surface roughness μin. R_a	15	60 (est.)	
Remarks:	Hardest ceramic	No burrs on through slots	Low carbon steel tool for engraving

TABLE 10.7-21—Continued

Work material:	Glass	Sintered Tungsten Carbide
Workpiece configuration.		
Abrasive type.	B_4C	B_4C
grit size:	600	220
percent concentration·		
Power supply frequency, kHz·	20	20
power, W.		
amplitude, in:		0.0025
Spindle thrust, lb:	0 33	3.5
Depth cut, in:	0 47	0 25
Cutting time, min:	0 0125 in/min	42
Wear ratio (work to tool)	9.1	
Tolerance, in·		
Surface roughness, μin R_a:		
Remarks.	0.014-inch OD, 0.007-inch ID stainless steel tube used for tool.	Mild steel tool used.

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Water Jet Machining—WJM 10.8

PROCESS SUMMARY

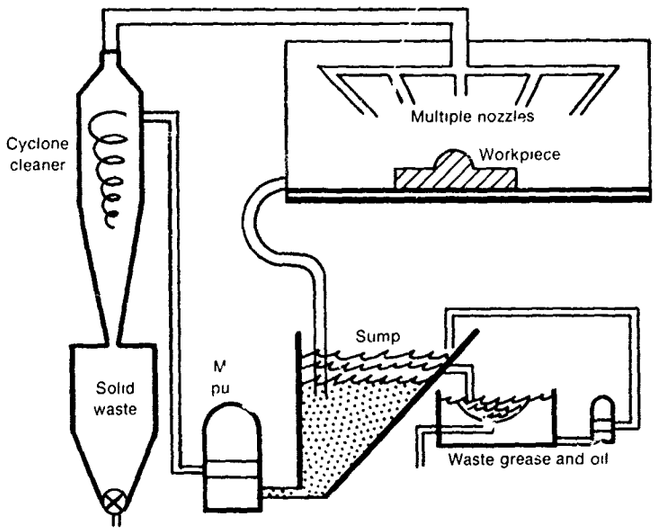


Figure 10.8–1 WJM schematic.

Principles

Water jet machining (WJM) is low pressure hydrodynamic machining The pressure range for WJM is an order of magnitude below that used in HDM There are two versions of WJM one for mining, tunneling and large pipe cleaning that operates in the region from 250 to 1000 psi [1 7 to 6.9 MPa]; and one, for smaller parts and production shop situations that uses pressures below 250 psi [1 7 MPa] The first version, or high-pressure range, is characterized by use of a pumped water supply with hoses and nozzles that generally are hand-directed. In the second version, more production-oriented and controlled equipment, such as that shown in figure 10.8-1, is involved In some instances, abrasives are added to the fluid flow to promote rapid cutting Single- or multiple-nozzle approachs to the workpiece depend on the size and number of parts per load. The principle is that WJM is high volume—not high pressure

Practical Applications

Production applications for WJM include descaling, deburring, surface cleaning, decorative finishing, nuclear decontamination, food utensil cleaning, internal deburring and degreasing Some polishing activities and preparations for precise inspection also have used WJM. Pipe cleaning and casting cleaning are good applications.

Operating Parameters

TABLE 10.8–1 Typical Values for WJM Operating Parameters

Pressure	30 to 250 psi [0 2 to 1.7 MPa] production 250 to 1000 psi [1.7 to 6.9 MPa] civil engineering
Fluid·	Water Water plus grit additives

10.8 Water Jet Machining—WJM

Material Removal Rates and Tolerances

Low pressure WJM is not a mass material removal process, it is a finishing, cleaning and deburring process. The higher pressure uses in civil engineering applications are outside the scope of a machinability handbook.

Surface Technology

A polished, scoured clean surface is typical. When abrasives are used, a light peening texture may occur. Motion in the workpiece or the nozzle is desirable because dwelling on one spot can result in grooving Oiling of iron bearing alloys is necessary to reduce rust formation after cleaning Shake-out or cleaning of crevices in the workpiece is necessary when grit loaded fluids are used.

Equipment and Tooling

Production equipment is available which offers adjustable nozzles in a splash chamber, pumps, filters and associated items in a single package. Portable equipment with flexible nozzles and lances also is commercially available.

Machining Characteristics

Suitable for cleaning large areas

SECTION 11

ELECTRICAL NONTRADITIONAL MACHINING OPERATIONS

11 1 Electrochemical Deburring—ECD 11–3
11.2 Electrochemical Discharge Grinding—ECDG 11–5
11 3 Electrochemical Grinding—ECG 11–9
11 4 Electrochemical Honing—ECH 11–23
11.5 Electrochemical Machining—ECM 11–25
11.6 Electrochemical Polishing—ECP 11–63
11.7 Electrochemical Sharpening—ECS 11–65
11.8 Electrochemical Turning—ECT 11–67
11.9 Electro-stream™—ES 11–69
11 10 Shaped Tube Electrolytic Machining—STEM™ 11–71

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Electrochemical Deburring—ECD 11.1

PROCESS SUMMARY

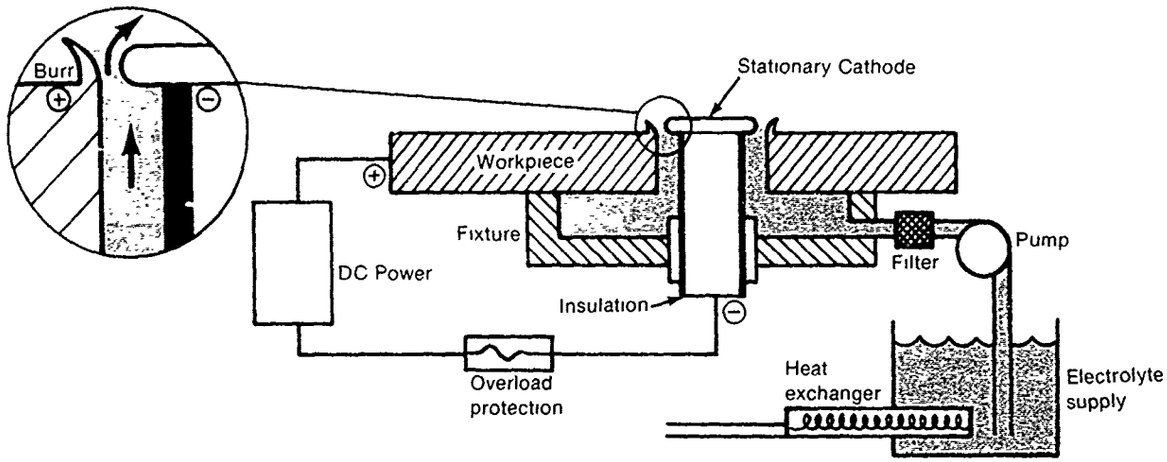


Figure 11.1-1 ECD schematic

Principles

Electrochemical deburring (ECD) is a special version of ECM (see figure 11.1-1). ECD was developed to remove burrs and fins or to round sharp corners. Anodic dissolution occurs on the workpiece burrs in the presence of a closely placed cathodic tool whose configuration matches the burred edge. Normally, only a small portion of the cathode is electrically exposed so a maximum concentration of the electrolytic action is attained. The electrolyte flow usually is arranged to carry away any burrs that may break loose from the workpiece during the cycle. Voltages are low, current densities are high, electrolyte flow rate is modest, and electrolyte types are similar to those used for ECM. The electrode (tool) is stationary, so equipment is simpler than that used for ECM. Cycle time is short for deburring. Longer cycle time produces a natural radiusing action.

Practical Applications

Almost any conductive material can be deburred or polished electrolytically. Most ECD is performed in seconds and is many times faster than hand deburring. The cycle time is limited by the load and unload parts of the operation. Drilling-burr removal is routine and involves only simple electrodes. Interior burrs, intersecting holes and internal fins can be deburred using precisely located electrodes. Applications include automotive connecting rods, gear teeth, blanking dies, valve parts, punch press blankings and machined pipe fittings. One 20-second ECD operation on automotive pistons simultaneously deburrs two oil ring slots, six piston wall oil holes, two piston pin oil holes and all weight bosses. The absence of mechanical contact or residual stress effects permits the use of ECD on thin parts or sections without fear of distortion or damage. Shallow reliefs (up to 0.030-inch [0.76 mm] deep) can also be produced.

Operating Parameters

TABLE 11.1-1 Typical Values for ECD Operating Parameters

Power supply	
type:	Direct current
voltage:	4 to 25 V
current.	50 to 500 A (approximately 10 to 15 A per linear inch of edge)
Gap	0.005 to 0.050 inch (generally 0.030 inch) [0.13 to 1.27mm—generally 0.76 mm]
Electrolyte	
types.	
frequently used:	1 to 2 lb/gal [120 to 240 g/L] NaCl
most used:	2 to 3 lb/gal [240 to 360 g/L] $NaNO_3$
rarely used:	2 to 4 lb/gal [240 to 480 g/L] $NaNO_2$
rarely used:	2 to 4 lb/gal [240 to 480 g/L] KCl
temperature:	90° to 110°F [32° to 42°C]
pressure:	15 to 50 psi [100 to 350 kPa]
flow.	1 to 4 gal/min [4 to 15 L/min] per 100 A
filters:	10 to 75 μm (microns)
Electrode material:	Brass or copper

Material Removal Rates and Tolerances

Most deburring occurs in 5 to 30 seconds, as shown in figures 11.1-2 and 11.1-3. The rate depends on work material, voltage, electrolyte, flow rate and tool design. Longer "on" times can produce a rounded corner in addition to deburring. Tolerances are in the range of ±0.0007 to ±0.002

11.1 Electrochemical Deburring—ECD

inch [±0.018 to ±0.050 mm]. The larger tolerances are associated with lower current densities and large operating gaps; however, the principal factor controlling accuracy is the "on" time. Automatic controls are needed to hold the best values.

Surface Technology

The highly focused electrolytic action produces smooth radii and surface roughness in the range of 8 to 16 microinches R_a [0.2 to 0.4 μm]. With high current densities, surface roughness can be 2 microinches R_a [0.05 μm]. Stray [illegible] will occur at some considerable distance from the [illegible]ing deburred. Shallow striations (less than .0001 inch [0.0025 mm]) can occur where turbulent flow, gas bubbles or insulation discontinuities are present. Some alloys with large, distinct grains can exhibit selective etching on a microscale, particularly in low current density areas adjacent to the principal focal point of the electrode. ECD is not stress-inducing and can remove some previously strained surface layers. Alloys with nonconductive grains, for example, silicon grains in aluminums alloys, can exhibit a pock-marked surface where these grains have fallen out.

Equipment and Tools

ECD equipment is smaller and less complex than that for ECM because feed motion is not required. Plastic tables or shallow tanks are arranged to accept the fixtures and to allow quick connections for electricity and electrolytes. Stainless steel fixtures and fittings are used to resist the corrosiveness of the electrolytes. Tooling and electrodes are tailored to conform to the configuration of the workpiece and the edges to be deburred. By properly insulating the cathode, effects on other exposed areas of the workpiece are reduced to negligible amounts. Power supplies range from 100 to 500 amperes, with multiples available if several parts are to be run concurrently. Automatic controls are desirable to secure repeatable results, particularly with the very short machining cycles. Multiple workpiece fixtures and automation of the ECD cycle are frequent. The cycle begins with closure of the lid or splash guard and placement of the electrode in correct relation to the workpiece. The cycle continues automatically from electrolyte-on, to current-on, through the cutting time to current-off, flushing, and opening of the lid. Hand-held tools for ECD also are available (see discussion of ECS, section 11.7). Electrolyte supplies, pumps and filters are sized to handle the flow rates. Flow rate depends on component size and fixtures, but usually ranges up to only a few hundred gallons because cycle times are so short.

ECD equipment for the 20-second operation on automotive pistons cited under "Practical Applications" was integrated into a transfer line that included cleaning, rinsing and oiling.

Machining Characteristics

It is essential that burr size and location be consistent. Burrs of excessive size or random location can cause shorts in the electrical circuits unless they are knocked off before the workpiece is placed in the close gaps with the electrode. Uniform results are typical with the fixed electrode positions. Variations in material properties will sometimes be revealed by the more uniform ECD action. The metal hydroxides in the used electrolyte need to be filtered out before the electrolyte is reused. This action minimizes metal hydroxide deposition on the workpiece or tools and promotes more uniform material removal rates. Disposal of sludge from the used electrolyte should be carried out in an environmentally sound manner.

SELECTED DATA

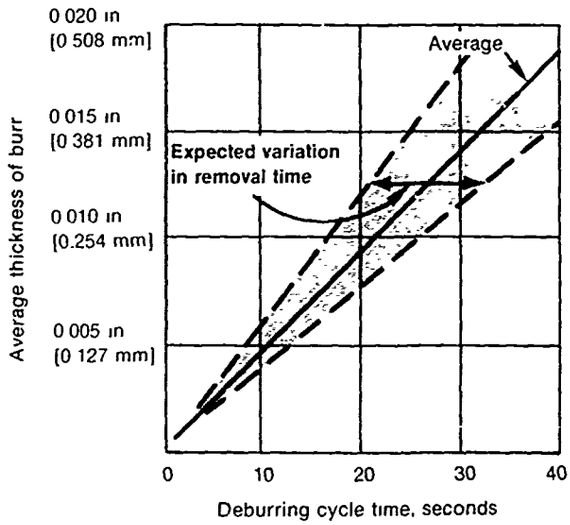


Figure 11.1-2 Burr removal rates for aluminum alloys. Thickness of burr is measured at root of burr. (D. W. Sickels, Electrochemical deburring—some capabilities and limitations, Technical paper MR76-133, Society of Manufacturing Engineers, Dearborn, MI, 1976, p. 10)

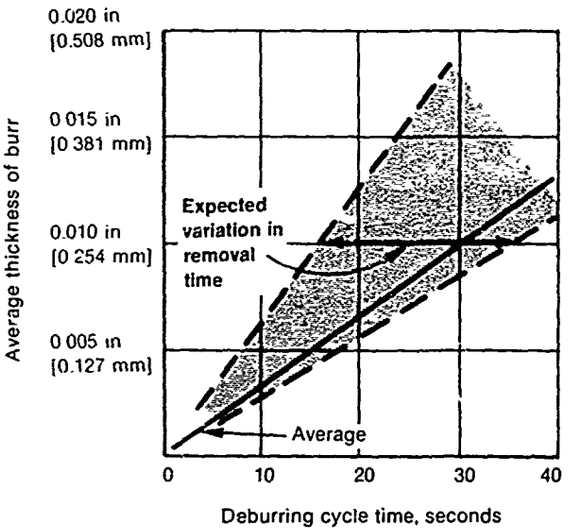


Figure 11.1-3 Burr removal rates for iron base alloys. Thickness of burr is measured at root of burr. (D. W. Sickels, p. 9)

Electrochemical Discharge Grinding—ECDG 11.2

PROCESS SUMMARY

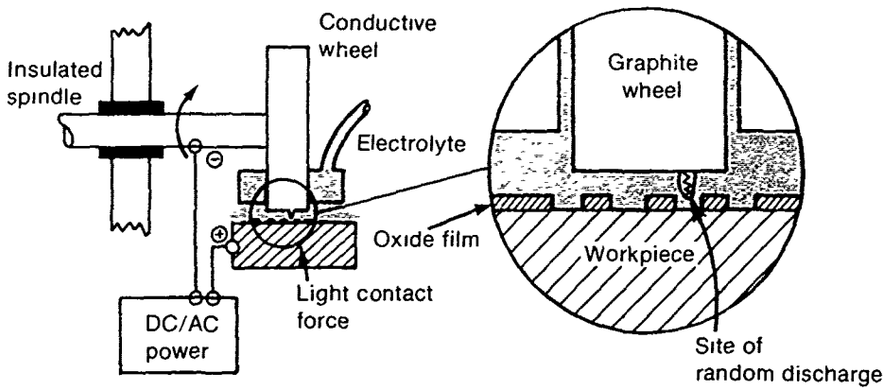


Figure 11.2-1 ECDG schematic

Principles

Electrochemical discharge grinding (ECDG) combines the features of both electrochemical and electrical discharge methods of material removal (see figure 11.2-1) ECDG has the arrangement and electrolytes of electrochemical grinding (ECG), but uses a graphite wheel without abrasive grains. The random spark discharge is generated through the insulating oxide film on the workpiece by the power generated in an alternating-current source or by a pulsating direct-current source The principal material removal comes from the electrolytic action of the low level direct-current voltages. The spark discharges erode the anodic films to allow the electrolytic action to continue. At increased operating levels, electrical discharge contributes to the material removal, as demonstrated in figure 11 2-2 There is no mechanical contact between the wheel and the workpiece; however, there are separating forces developed by the compression of the electrolyte in the space between the wheel and the workpiece. Careful electrolyte control is required to assure its placement between the workpiece and the wheel and to prevent boiling and possible severe arcing. Sometimes the process is called ECDM, electrochemical discharge machining.

Practical Applications

The workpiece must be an electrically conductive material. As with ECM, the hardness of the workpiece does not affect the material removal rates, and almost any conductive material can be cut Single-point carbide disposable-insert grinding or resharpening is done by ECDG. Plunge, face and surface grinding are all performed. Thin or delicate profiles can be form ground. The electrolytic action produces a burr-free surface. Circular forms that need to be stress free are good applications, as is the machining of honeycomb materials. The low cost wheel and the ease with which it can be formed for intricate profile grinding are distinct advantages. Careful economic comparisons between ECDG and ECG should be made before completing an application study.

11.2 Electrochemical Discharge Grinding—ECDG

Operating Parameters

TABLE 11.2–1 Typical Values for ECDG Operating Parameters

Power supply		
type.	Pulsating dc	ac
frequency:	120 Hz	60 Hz
voltage·	4 to 12 V (8 optimum)	8 to 12 V
current:	200 to 1000 A	200 to 500 A
Electrolyte		
type.	NaCl, $NaNO_3$ proprietary neutral salts	
concentration:	1½ to 2 lb/gal [180 to 240 g/L]	
temperature (inlet):	80° to 100°F [27° to 38°C]	
Wheel		
type:	Graphite, typically 300 mesh	
speed:	4000 to 6000 fpm [1200 to 1800 m/min] (Lower speeds do not promote good electrolyte flow and permit gas bubbles to become too large, thus inhibiting maximum current densities—see figure 11.2–3.)	
Operating gap.	0.0005 to 0.0015 inch [0.013 to 0.038 mm] (figure 11 2–4)	
Pressure between wheel and workpiece.	5 to 20 psi [35 to 140 kPa]	
Current density for		
carbides:	600 A/in² [1 A/mm²] maximum	
other metals.	800 A/in² [1 3 A/mm²] maximum	
steel, using pulsed dc:	1200 A/in² [2.0 A/mm²] maximum (Excessive current density can overheat workpiece and/or wheel)	
Feed rates*		
plunge grinding, carbide:	0.020 in/min [0 5 mm/min]	
plunge grinding, steel:	0.060 in/min [1 5 mm/min]	
surface grinding, carbide.	0.15 in/min [3.8 mm/min]	
surface grinding, steel:	0.50 in/min [12.7 mm/min]	
Wheel wear ratios		
ac power·	7:1 (carbide or steel)	
dc power:	40:1 (steel)	

*For 575 A/in² [0.9 A/mm²] on an 8-inch [200 mm] diameter wheel
Surface grinding at 0 10 inch [2 5 mm] depth of cut.

Material Removal Rates and Tolerances

ECDG will remove about one cubic inch [16 cm³] of tool steel per hour—about 5 times faster than EDG while using 10 to 15 times as much current. Dimensional accuracy is less than that from EDG and is typically ±0.0005 inch [±0.013 mm] with close control and ±0.001 inch [±0.025 mm] for routine production. While a typical depth of cut is one-half inch [12.5 mm] when machining at 200 amperes, the cubic inches per minute metal removal rate is 0.006 [0.1 cm³/min] for carbide workpieces and 0.015 [0.25 cm³/min] for steel workpieces. Single-point carbide disposable inserts have been ground to a depth of 0.010 inch [0.25 mm] at the rate of one insert per minute. Carbide thread chasers have been ground with a mean thread height deviation of ±0.0003 inch [±0.008 mm] and pitch deviation of ±0.00015 inch [±0.004 mm]. The accuracy is primarily a function of the degree to which the electrolyte film is uniform. Special scrapers are needed to control the electrolyte flow and to prevent air films.

Surface Technology

Surface roughness values of 5 to 15 microinches R_a [0.13 to 0.38 μm] for carbide workpieces and 15 to 30 microinches R_a [0.38 to 0.76 μm] for steel workpieces can be expected. The surfaces are sometimes pitted with minute craters from the electrical discharge if the voltages used are too high. (Too-high voltage also deteriorates the wear ratio.) The electrolytic dissolution promotes stress-free material removal action and burr-free edges.

Equipment and Tools

Commercial equipment in the range from 20 to 1000 amperes is available on special engineering order. Tooling involves the electrolyte flow control so as to obtain a uniformly thick film between the workpiece and the wheel. Conforming graphite or plastic film scrapers are essential to tolerance and repeatability control. A sufficient flood of filtered electrolyte is essential to high material removal rates and to the prevention of excessive temperatures, gas bubbles or boiling in the working gap. Fixtures should be made of stainless steel, plastic, or materials compatible with the corrosiveness of the electrolyte.

Machining Characteristics

Wheel-to-workpiece wear ratios are dependent upon the type of power supply, the voltage, the grade of graphite and the uniformity of electrolyte film. Figure 11.2-5 demonstrates the relationship between wheel wear and voltage.

SELECTED DATA

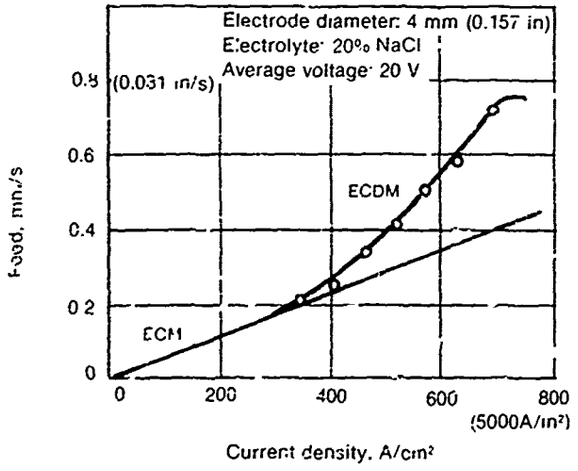


Figure 11.2-2 Feed rate versus current density in drilling steel plate with ECDM. (M. Kubota, Metal removal in ECDM, *ISEM-5 Proceedings, International Symposium for Electromachining*, Zurich, Switzerland, 1977, p. 218)

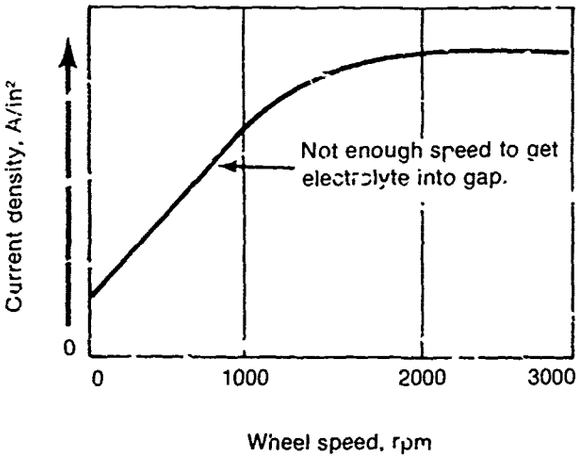


Figure 11.2-3 Relationship between current density and wheel speed. (W. G. Voorhees, Electrochemical discharge machining, Technical paper MR67-165, Society of Manufacturing Engineers, Dearborn, MI, 1967, p. 7)

11.2 Electrochemical Discharge Grinding—ECDG

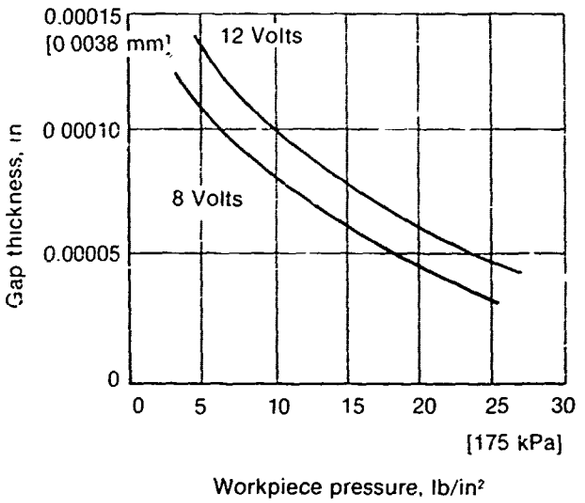


Figure 11.2–4 Relationship between gap thickness, workpiece pressure and gap voltage (W G Voorhees, p 7)

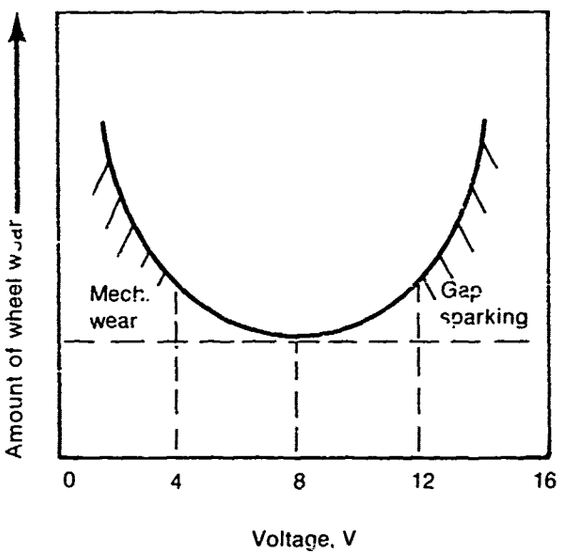


Figure 11.2–5 Effect of gap voltage on wheel wear. (W G. Voorhees, p. 7)

PROCESS SUMMARY

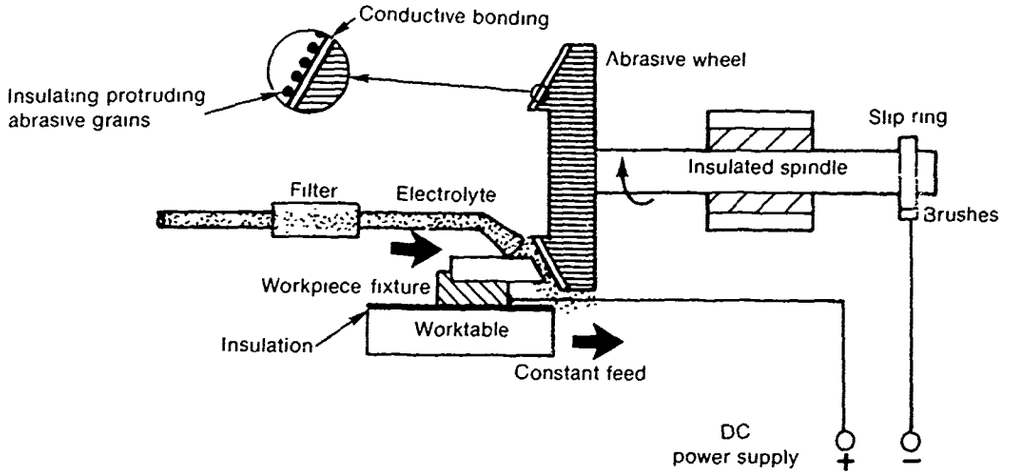


Figure 11.3–1 ECG schematic.

Principles

Electrochemical grinding (ECG) is a special form of electrochemical machining in which the conductive workpiece material is dissolved by anodic action, and any resulting films are removed by a rotating, conductive, abrasive wheel (see figure 11.3-1) The abrasive grains protruding from the wheel form the insulating electrical gap between the wheel and the workpiece. This gap must be filled with the electrolyte at all times The conductive wheel uses conventional abrasives—aluminum oxide (because it is nonconductive) or diamond (for intricate shapes)—but lasts substantially longer than wheels used in conventional grinding. The reason for this is that the bulk of the material removal (95 to 98 percent) occurs by deplating, while only a small amount (2 to 5 percent) occurs by abrasive mechanical action Maximum wheel contact arc lengths are about 3/4 to 1 inch [19 to 25 mm] to prevent overheating the electrolyte. The fastest material removal is obtained by using the highest attainable current densities without boiling the electrolyte The corrosive salts used as electrolytes should be filtered, and flow rate should be controlled for the best process control.

Practical Applications

Face, plunge, cone or contour grinding are usual ECG applications on high-strength, conductive materials, regardless of hardness. Almost any conductive material can be ground electrochemically. Low wheel wear, infrequent dressing, minimal forces on the workpiece and automatic deburring are characteristic. Sharpening, shaping or resharpening tungsten carbide tool bits, contouring fragile honeycomb parts, and cutting surgical needles and thin-wall tubing are practical Grinding hard, tough materials without heat checks or burrs is frequently done. Inner corner radii are limited to 0.010 to 0.015 inch [0 25 to 0 38 mm] Precision and fine finishes are combined with more rapid cutting, freedom from burrs and absence of residual stress or distortion. ECG is performed with 1/7 or less of the grinding wheel wear of conventional grinding. It also compares favorably with conventional milling and grinding (see table 11.3-5).

Operating Parameters

TABLE 11.3–1 Typical Values for ECG Operating Parameters

Power supply	
type:	Direct current
voltage:	4 to 14 V
current:	50 to 3,000 A
Gap:	0.001 inch [0.025 mm] (about equal to protrusion of abrasive grains)
Electrolyte	
types:	
frequently used:	$NaNO_3$, 1 to 2 lb/gal [120 to 240 g/L]
rarely used:	KNO_3, 1½ to 2 lb/gal [180 to 240 g/L]
rarely used:	NaCl, ½ to 1½ lb/gal [60 to 180 g/L]
temperature:	90° to 110°F [26° to 42°C]
pressure:	2 to 10 psi [14 to 70 kPa]
filters:	50 to 100 micrometers
flow control:	Close-fitting nozzle with air scraper
Abrasive wheel	
type:	Conductive
abrasive:	Al_2O_3 or diamond grit
speed:	4,000 to 7,000 fpm [1,200 to 2,100 m/min]
Feed rate and depth cut:	Figure 11.3–3
Length of contact.	Up to 0 75 inch [19 mm]. Limit length to prevent boiling in electrolyte. See also figure 11 3–3.

11.3 Electrochemical Grinding—ECG

Material Removal Rates and Tolerances

The material removal rate is proportional to the current density. The current density is limited by the anodic dissolution rate for a particular alloy-electrolyte system and the boiling point of the electrolyte. A convenient value for most common materials is 0.010 cubic inch per minute [0.16 cm^3/min] per 100 amperes of current. A plunge grinding feed rate of 0.050 inch per minute [1.27 mm/min] is attained at 500 amperes per square inch [77.5 A/cm^2], while surface grinding operates at 1.0 inch per minute [25.4 mm/min] with a 0.010 inch [0.25 mm] depth of cut at 1000 amperes per square inch [155 A/cm^2]. Size control is typically ±0.001 inch [±0.025 mm] and is attainable in a one-pass cut. Accuracies to ±0.0002 inch [±0.005 mm] can be achieved with the final pass without electrolytic action. Outside corners usually have a radius about 0.001 inch [0.025 mm]. Inside corners have a limit of 0.010- to 0.015-inch [0.25 to 0.38 mm] radius. Removal rates are 5 to 10 times those for conventional grinding on hard materials (Rockwell C45 and up).

Surface Technology

Surface finishes improve with increasing current densities and higher feed rates. Roughness values of 8 to 32 microinches R_a [0.2 to 0.8 μm] are common, with 1 to 4 microinches R_a [0.025 to 0.1 μm] attainable. The surface texture is similar to that obtained with a metallographic polish. Workpiece hardness is not a factor; however, the material type can affect the range of roughness values. The surface is free from process-induced residual stress and there is no heat-affected zone. Both of these effects contribute to the production of workpieces with high surface integrity.

Equipment and Tools

Grinding machine construction must be rigid enough to maintain precision under the deflecting forces which can reach 150 psi [1 MPa] between the workpiece and the wheel. The spindle must be insulated and capable of conducting the low-voltage, high-current d-c power to the wheel. Associated equipment is required to store, pressurize, filter and withstand the corrosive electrolytes. Controls, fixtures and mechanical and electrical systems must be made of suitable material or coated so as to be capable of operating in the salt mist environment. Conversion kits to convert mechanical grinders are available. Wheels must be conductive and must use an insulating grain. Electrolyte nozzles should be close fitting and should be made of Plexiglas or equivalent dielectric material (see table 11.3-4). Workpiece fixtures should be made of copper, copper-base alloys or 300-series stainless steel and should be constructed such that all cathodic components remain electrically insulated from anodic components during the ECG operation. The wheels must have the correct abrasive qualities of the insulating grit (silicon carbide and some forms of Borazon cannot be used because they are electrically conductive.)

Machining Characteristics and Precautions

It is necessary to "condition" any ECG wheel to remove the metal matrix and to allow the nonconductive abrasive particles to protrude (see table 11.3-4). To accommodate the usually longer runs between wheel dressings, truing of the wheel should be more precise than that for conventional grinding—0.0002 to 0.0005 inch TIR [0.005 to 0.013 mm].

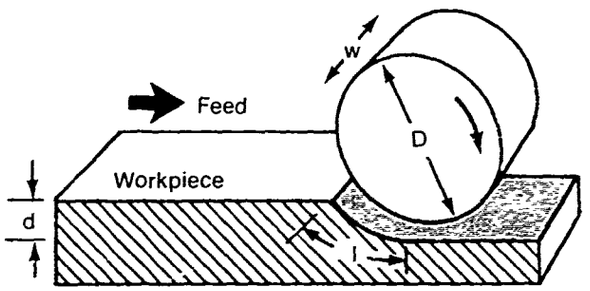
Handling and storage of the electrolytes should be done with care and strict attention to the cautions pertaining to the particular chemicals (see table 11.5-6, ECM). A moderate fire hazard exists when dry $NaNO_3$ is mixed with organic materials. With their heavy metal and salt content, the disposal of the used electrolytes needs careful, environmentally sound planning.

Areas adjacent to the current gap are exposed to the conductive spray and may be slightly eroded or pitted by the low current densities present there. Appropriate insulation in the tooling is required to avoid bimetal electrolytic corrosion. NaCl electrolytes are rarely used in ECG because they have strong corrosive effects on machine components. Citrates, tartrates or proprietary chemicals frequently are added to the electrolytes and can aid machining while reducing corrosiveness. A thorough washdown of the equipment and tools at the end of each day or each period of use is a good preventive maintenance practice. Workpieces should also be well rinsed after ECG, and some materials should be checked for possible adverse metallurgical reaction to the electrolytes.

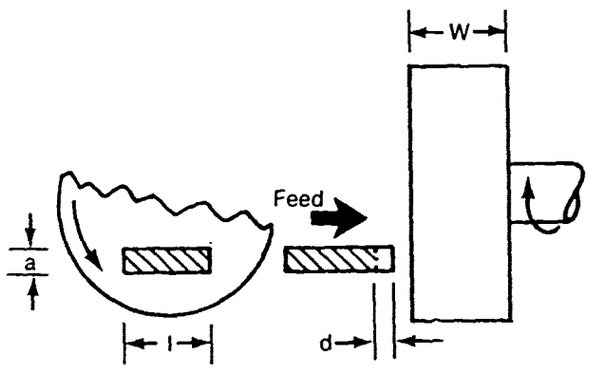
Spindle current for the a-c drive motor is a good indication of the amount of mechanical grinding during ECG. An increase in current to 125 percent of the no-load value for roughing ECG or to 115 percent of the no-load value for finishing ECG is a reasonable upper limit for the amount of grinding. The d-c operating current should be selected such that resistive overheating does not occur in the workpiece.

SELECTED DATA

There are several valid techniques for selecting operating parameters for ECG. The steps in table 11 3-2 are recommended as one logical sequence Supporting data come from the other figures and tables in accordance with the terms as explained in figure 11 3-2.



SURFACE ECG



FACE PLUNGE ECG

Figure 11.3-2 Parameter terminology for surface and face plunge ECG.

11.3 Electrochemical Grinding—ECG

TABLE 11.3-2 Steps To Select ECG Operating Parameters

ITEM	SURFACE ECG	FACE PLUNGE ECG
1 Select wheel type to suit work material	Table 11 3-3	Table 11 3-3
2 Select size of wheel	Largest possible diameter for particular part shape	Largest possible diameter for particular part shape
3. Select wheel speed	4,000 to 7,000 fpm [1,200 to 2,100 m/min]. Too low, electrolyte not inserted as well: too high, no extra benefits	4,000 to 7,000 fpm [1 200 to 2,100 m/min]. Too low, electrolyte not inserted as well: too high, no extra benefits.
4 Select electrolyte, mix	Table 11.3-3	Table 11 3-3
5. Select electrolyte specific gravity test value and operating temperature	Figures 11.5-10, 11.5-11, 11.5-12 in ECM section	Figures 11.5-10, 11 5-11, 11.5-12 in ECM section
6 Select current density for particular material (A/in^2) [A/cm^2]	Table 11.3-3 (or from trial or laboratory testing) (or work from generalized material removal rate—see item 13) The current density in the workpiece must be low enough to prevent overheating.	Table 11.3-3 (or from trial or laboratory testing) (or work from generalized material removal rate—see item 13) The current density in the workpiece must be low enough to prevent overheating
7. Determine depth of cut (d)	Maximum to suit part configuration and wheel diameter	Not applicable
8. Determine contact length (l) (maximum ¾ to 1 inch [19 to 25 mm] electrolyte flow path)	Figure 11.3-3	Figure 11.3-2
9 Calculate contact area	l times w (if slot and side cutting also, then area on side of wheels must be included—see figure 11.3-8)	l times a
10 Calculate current required	Current density times contact area	Current density times contact area
11. Select voltage setting (4 to 12 V dc approx.)	Set to attain required current during a trial cut after full contact made. Do not increase to point any sparking occurs Final setting to be ½ volt less than value that gives sparking with the correct value of spindle current, item 12. (See also figures 11.3-6 and 11.3-7.)	Set to attain required current during a trial cut after full contact made. Do not increase to point any sparking occurs Final setting to be ½ volt less than value that gives sparking with the correct value of spindle current, item 12. (See also figures 11.3-4 and 11.3-5.)
12. Check spindle current	Full contact spindle current should be only a little larger than the no-load current so as to keep the mechanical grinding less than 5% of the total metal removal rate. A value of 115% for finishing ECG or 125% for roughing ECG is a practical limit.	Full contact spindle current should be only a little larger than the no-load current so as to keep the mechanical grinding less than 5% of the total metal removal rate. A value of 115% for finishing ECG or 125% for roughing ECG is a practical limit.
13. Material removal rate (MRR)	Use generalized value of 0.010 $in^3/min/100$ A [164 $mm^3/min/100$ A] as a starting point or refine as in ECM to specific alloy dissolution rate and multiply by current.	Use generalized value of 0.010 in^3 min/100 A [164 $mm^3/min/100$ A] as a starting point or refine as in ECM to specific alloy dissolution rate and multiply by current.
14 Volume metal to be removed, in^3 [mm^3]	d times w times length cut	l times a times d
15. Time for cut or per pass	Volume divided by MRR	Volume divided by MRR
16 Feed rate	Figure 11 3-3	Current density times MRR

TABLE 11.3-3 Recommended Parameters for ECG of Various Materials

WORK MATERIAL	WHEEL TYPE	ELECTROLYTE*			MAXIMUM CURRENT DENSITY†	
		Base Chemical	lb/gal H_2O	g/L H_2O	A/in²	A/cm²
Straight tungsten carbide	Diamond	KNO_3	1.5-1.7	180-200	500	78
Tantalum, tungsten carbide grades	Diamond	KNO_3	1.5-1.7	180-200	500	78
High speed steel	Diamond	$NaNO_3$	1.0-1.5	120-180	500	78
Tungsten	Diamond	KOH or NaOH	1.0-1.5	120-180	500	78
Low carbon steel	Aluminum oxide	KNO_3 (90%) + KNO_2 (10%)	0.5-1.0	60-120	1000	155
High carbon steel	Aluminum oxide	$NaNO_3$	1.0-1.5	120-180	1000	155
Stainless steel	Aluminum oxide	$NaNO_3$	1.5-1.7	180-200	500	78
Silicon iron	Aluminum oxide	NaCl	1.0-1.5	120-180	500	78
Copper alloys	Aluminum oxide	$NaNO_3$ or KNO_3	1.5-1.7	180-200	1500	233
Aluminum alloys	Aluminum oxide	$NaNO_3$	1.0-1.2	120-140	1500	233
Titanium alloys	Aluminum oxide	$NaNO_3$	1.0-1.2	120-140	1000	155
A-286	Aluminum oxide	$NaNO_3$	1.0-1.2	120-140	750	116
Hastelloy alloy X	Aluminum oxide	$NaNO_3$	1.0-1.2	120-140	750	116
M252	Aluminum oxide	$NaNO_3$	1.0-1.2	120-140	750	116
Udimet 500, 700	Aluminum oxide	$NaNO_3$ or NaCl*	0.9-1.0	110-120	750	116
Waspaloy	Aluminum oxide	$NaNO_3$	1.0-1.2	120-140	750	116
Inconel	Aluminum oxide	$NaNO_3$	1.0-1.2	120-140	750	116
Rene 41	Aluminum oxide	$NaNO_3$	1.8-2.0	180-230	500	78
Rene 80	Aluminum oxide	$NaNO_3$	1.5-1.9	120-140	500	78
Nickel alloys	Aluminum oxide	$NaNO_3$	1.0-1.2	120-140	750	116
Cobalt alloys	Aluminum oxide	$NaNO_3$	1.0-1.2	60- 80	500	78
HS-31 (X-40)	Aluminum oxide	$NaNO_3$ + NaCl*	0.5-0.7	60- 80	500	78
Zirconium alloys	Aluminum oxide	$NaNO_3$	1.0-1.5	120-180	750	116
Stellite	Aluminum oxide	$NaNO_3$	1.8-2.0	210-240	500	78

*There are many proprietary mixtures or additives to the base chemicals that have desirable effects on specific alloys and restrain the corrosion of equipment. These are recommended for initial trials. Note that NaCl is especially corrosive

†Density may be limited by possibility of overheating workpiece

11.3 Electrochemical Grinding—ECG

TABLE 11.3–4 Recommended Procedures for Conditioning the Wheel, Maintaining the Electrolyte, and Fitting the Nozzle in ECG Operations

ECG wheels require 'conditioning" after dressing to remove copper binder and allow nonconductive particles of aluminum oxide or diamond to protrude Attention to electrolyte co dition and flow nozzle on a regular basis is also recommended

Wheel mounting procedure recommendations

1 After removing worn-out wheel, clean flanges and spindle with warm, clean water and dry thoroughly Check for any burrs on bearing surfaces of flanges
2 Clean bearing surfaces and holes of flanges with an abrasive fabric, then blow clean with air to remove any abrasive particles This is important for proper electrical conductivity between flanges and wheel
3 Mount wheel At this point, only hand-tighten flange nut
4. Indicate wheel face to within 0 001 inch [0 025 mm] TIR (total indicated runout), this is accomplished by trial and error Use piece of wood to tap wheel into position Tighten flanges with wrench and re-check TIR. 'f wheel has moved repeat procedure

Conditioning cutting face of wheel

1 Set source voltage at 4 to 5 volts.
2 Set spark suppress at maximum setting (if such control exists on power supply)
3 Start wheel rotation and full electrolyte flow
4 Plunge grind into a piece of scrap steel. Plunge into steel slowly until ampere meter stabilizes
5. Increase voltage and feed until sparking occurs
6 Continue until cutting face and wheel has a dull gray or charcoal appearance
7 Wheel is now ready to use
8 Return spark control to normal setting

Electrolyte checks:

If machine is not equipped with a coolant filter, electrolyte should be changed once a week, or when mounting a new wheel Check electrolyte nozzles to ensure proper flow on all areas of wheel

For cutoff wheels, electrolyte should flow evenly under full available pressure on each side of wheel and on wheel periphery

Nozzle fitting:

The fitting of the nozzle is very important since it will help to confine and direct the electrolyte into the working gap between the wheel and workpiece contact area A properly selected and fitted nozzle will also help to reduce "stray machining" caused by a combination of excessive electrolyte spray and uncontrolled current flow

The point at which the wheel enters into the nozzle must be tightly fitted against the O.D surface of the wheel. This will break up the air curtain around the periphery of the "spinning" wheel. The air curtain would seriously restrict the current flow between the anode and cathode in the working gap. The wheel will pick up the electrolyte by traveling through the supply line. It is also good practice to relieve the inside of the nozzle chamber to eliminate any possible wiping action between wheel and nozzle

TABLE 11.3–5 Comparison of ECG to Precision Conventional Milling and Grinding

MATERIAL	STOCK REMOVAL (MILLING)	STOCK REMOVAL (GRINDING)	TOOLING COSTS & REPLACEMENT	SIZE CONTROL	PRODUCTION OF FRAGILE PARTS	POTENTIAL OF HEAT DAMAGE	QUALITY OF SURFACE FINISH	PROBLEMS WITH BURRS
Machinery steel	–	=	–	–	+	=	=	+
Tool steel, soft	–	=	–	–	+	+	=	+
Tool steel, hard	+	+	–	–	+	+	=	+
Cast iron	–	–	–	–	+	=	–	=
Copper	–	+	–	=	+	=	+	+
Brass	–	+	–	=	+	=	=	+
Aluminum	–	–	–	–	+	=	–	+
Tungsten	–	+	–	=	+	+	+	+
Tungsten carbide	+	+	+	=	+	+	+	=
Beryllium	–	=	–	–	=	=	–	+
300 stainless	–	+	+	=	+	+	+	+
400 stainless	–	+	+	=	+	+	+	+
Titanium	–	=	=	=	+	+	=	+
A-236	–	+	+	=	+	+	=	+
Waspaloy	+	+	+	=	+	+	+	+
Inconel 718	+	+	+	=	+	+	+	+
Inconel X	+	+	+	=	+	+	+	+
Rene 41	+	+	+	=	+	+	+	+
HS-21	+	+	+	+	+	+	=	=
Hastelloy alloy X	+	+	+	=	+	+	=	+
PWA 1004	+	+	+	=	+	+	=	+
PWA 689	+	+	+	=	+	+	=	+
AMS 5668	=	+	+	=	+	+	=	+
Udimet 500	+	+	+	=	+	+	+	+
Udimet 700	+	+	+	=	+	+	+	+
Greek Ascoloy	–	=	+	=	+	+	=	+
PWA 90	+	+	+	=	+	+	+	+

Legend = Processes about equal
– ECG inferior to conventional machining
+ ECG superior to conventional machining

SOURCE R R Bradi, Basics of electrochemical grinding, *American Machinist* 118 (April 24, 1974), p 48

NOTE In general, ECG superiority increases with hardness or toughness of material

11.3 Electrochemical Grinding—ECG

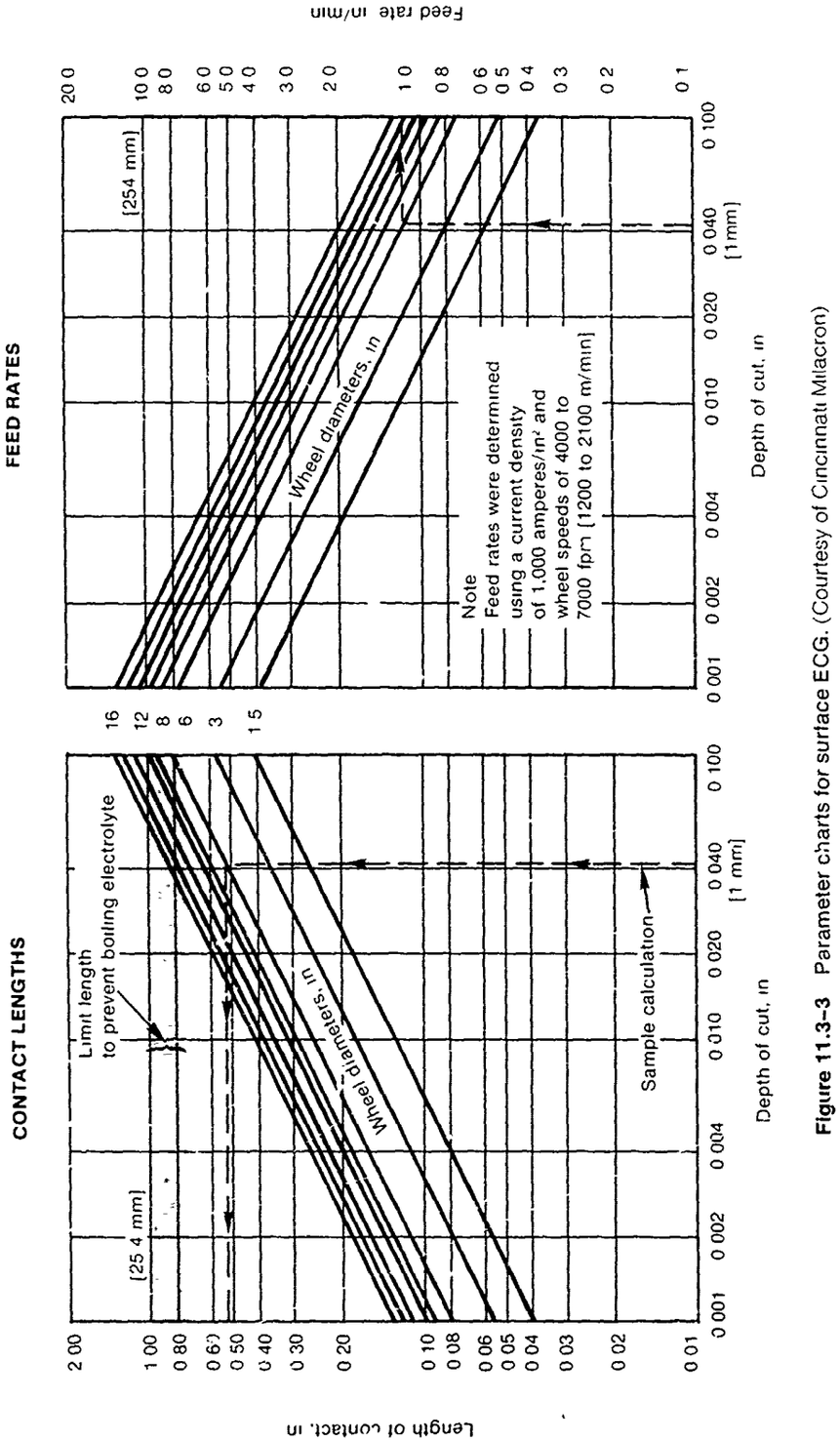


Figure 11.3-3 Parameter charts for surface ECG. (Courtesy of Cincinnati Milacron)

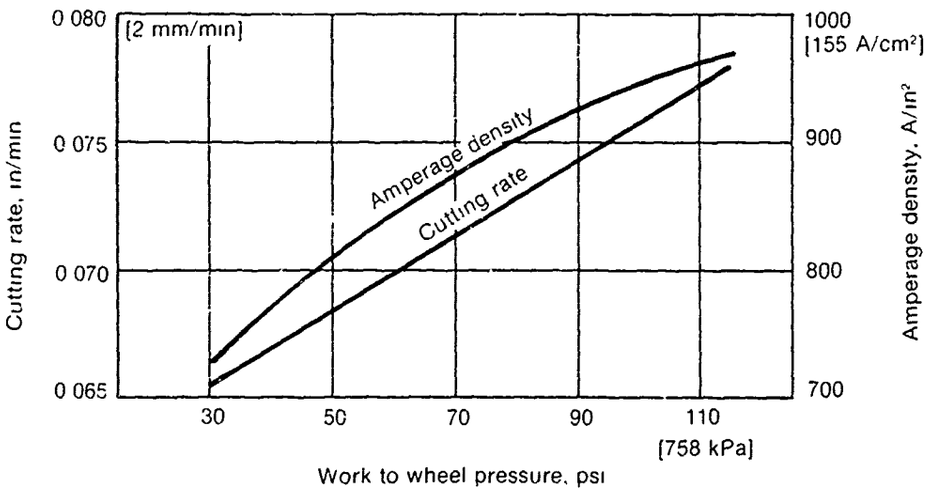


Figure 11.3–4 Effects of work to wheel pressure in face ECG on M2 tool steel with aluminum oxide wheel (J R Thompson, Operating parameters in electrochemical grinding with aluminum oxide wheels. *New Developments in Grinding*, Pittsburgh, PA Carnegie Press, 1972, p 793–812)

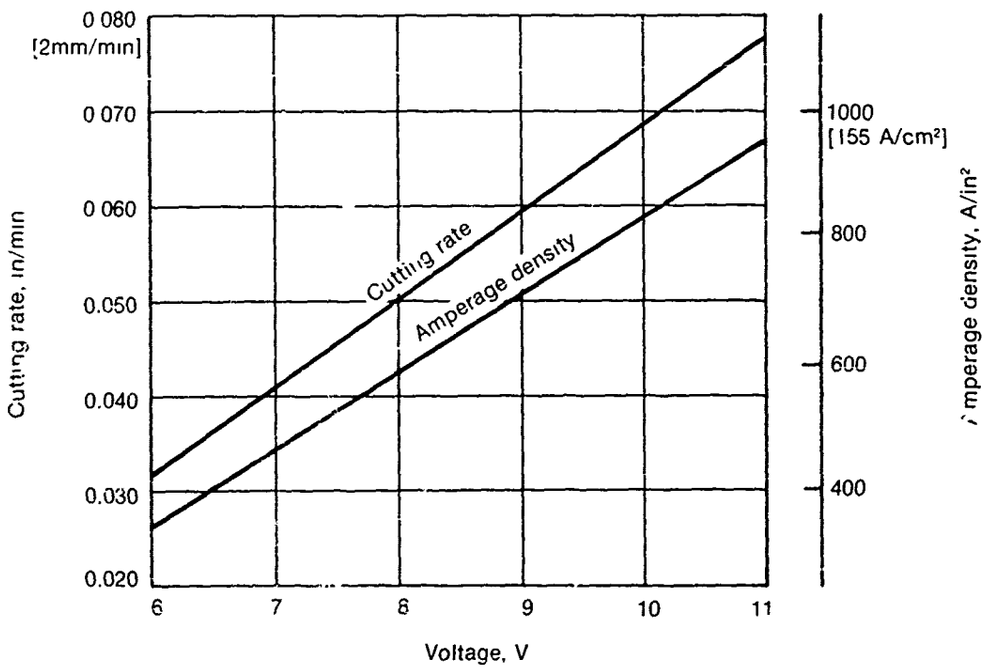


Figure 11.3–5 Effects of voltage in face ECG on M2 tool steel with aluminum oxide wheel. (J. R Thompson, p. 811)

11.3 Electrochemical Grinding—ECG

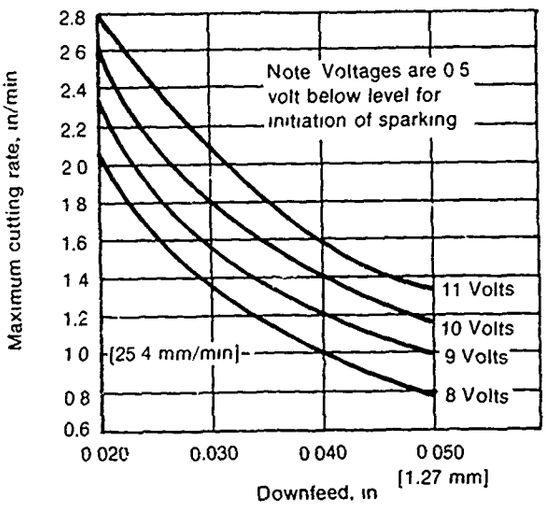


Figure 11.3–6 Maximum cutting rate as a function of voltage and downfeed for surface ECG on M2 tool steel with aluminum oxide wheel. (J. R. Thompson, p. 812)

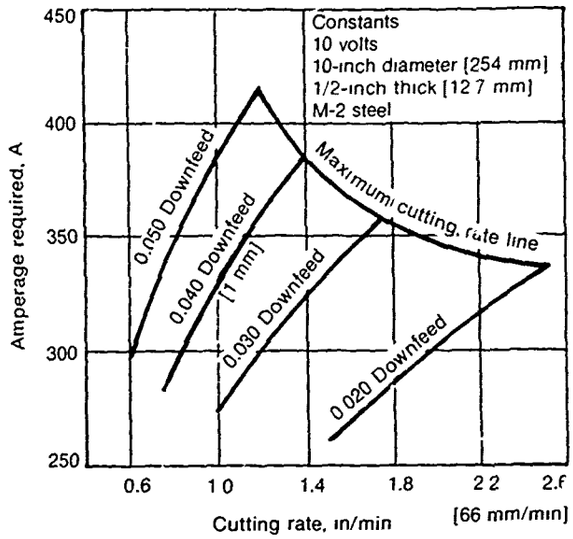
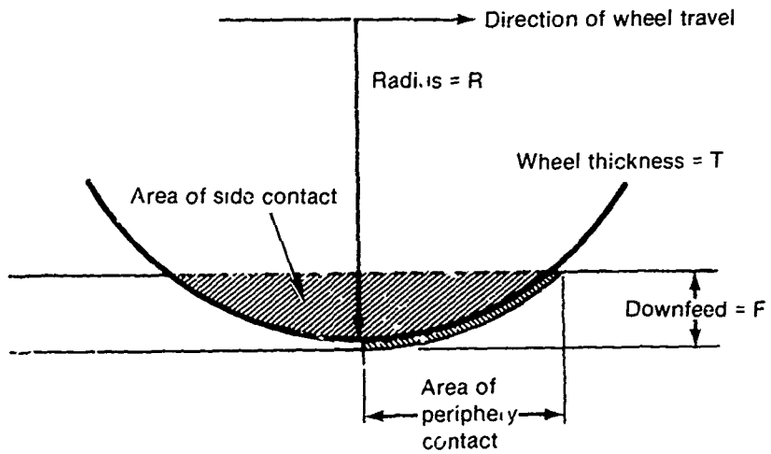


Figure 11.3–7 Family of operating curves and maximum cutting rates for surface ECG on M2 tool steel with aluminum oxide wheels. (J. R. Thompson, p. 812)

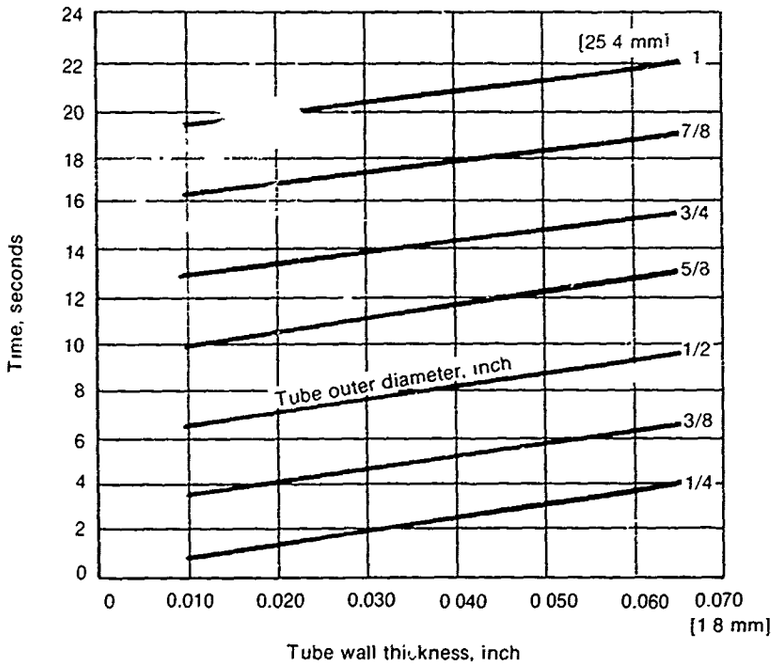


Total area of contact = Area of periphery contact + Area of side contact

$$\text{Area} = \frac{T\pi R}{180} \cdot \arccos\left(\frac{R-r}{R}\right) + 2\left[\frac{\pi R^2}{180}\arccos\left(\frac{R-F}{R}\right) - (R-F)\sqrt{2RF-F^2}\right]$$

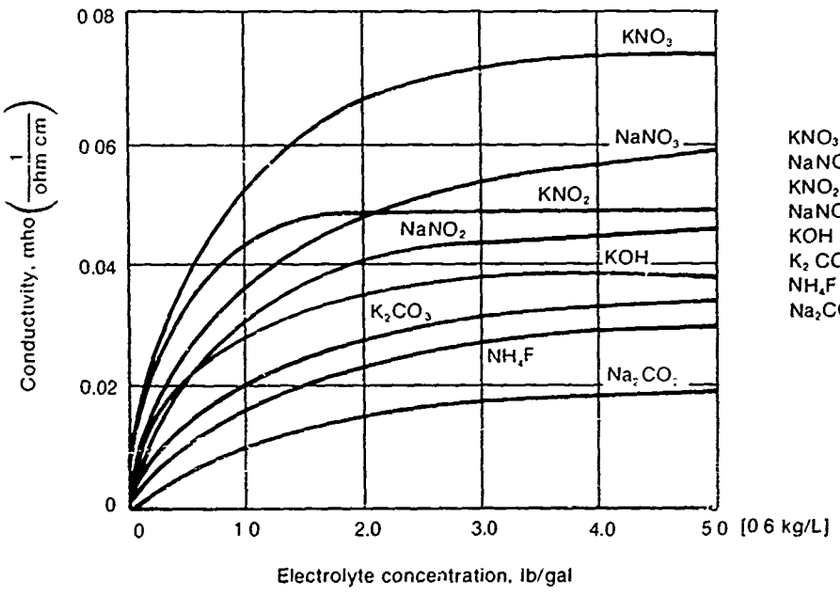
(arccos is in degrees, not radians)

Figure 11.3–8 Calculation of contact area of wheel and workpiece for surface ECG of slots. (J. R. Thompson, p. 810)



Burr-free distortionless tubing cut off by ECG is easily accomplished for type 304 stainless steel The data also are applicable to many other alloys to obtain rough production rates even though the electrolytic dissolution rates will vary slightly with composition (see ECM section 11 5) For well radiused cut ends, a spindle dwell time of 2 to 5 seconds can be added at the end of the charted cutting time These cutting times are the fastest burr-free rate without regard for wheel wear

Figure 11.3–9 ECG cutoff operation for type 304 stainless steel tubing. Maximum cutting rates for various tube diameters and wall thicknesses. (Courtesy of Everite Machine Products Company)



KNO_3 Potassium nitrate
$NaNO_3$ Sodium nitrate
KNO_2 Potassium nitrite
$NaNO_2$ Sodium nitrite
KOH Potassium hydroxide
K_2CO_3 Potassium carbonate
NH_4F Ammonium Fluoride
Na_2CO_3 Sodium carbonate

Figure 11.3–10 Conductivity versus concentration for ECG electrolytes (Courtesy of Anocut Engineering Company)

11.3 Electrochemical Grinding—ECG

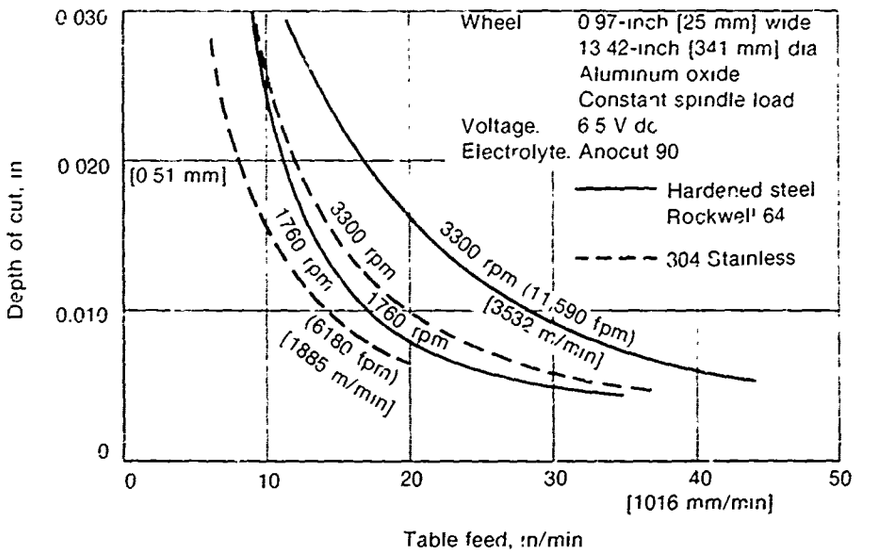


Figure 11.3–11 Effect of wheel speed in ECG of two work materials. Note: Wheel speeds are somewhat higher than the typical 4000 to 7000 fpm. (L A Williams, III. Electrochemical grinding Technical paper MR67-649 Society of Manufacturing Engineers, Dearborn, MI, 1967, p 17)

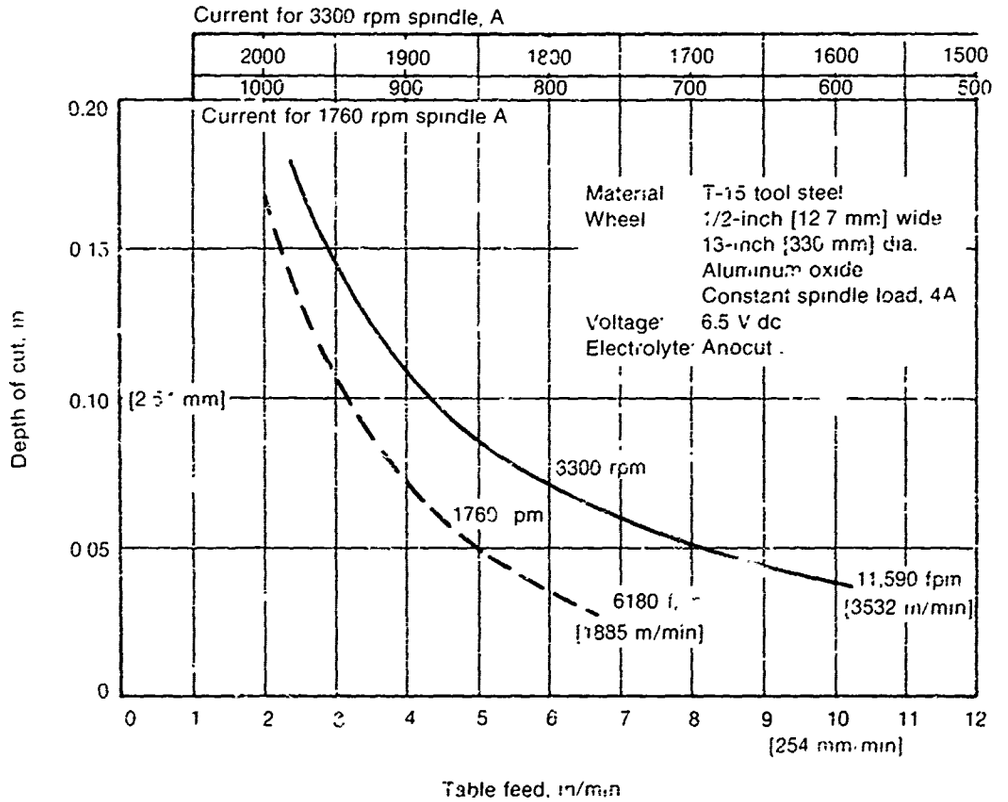
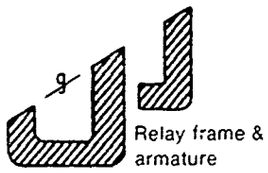
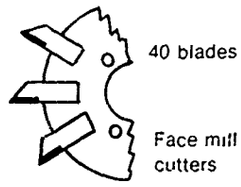
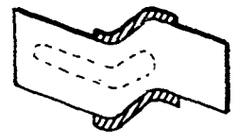


Figure 11.3–12 Effect of wheel speed in ECG of T15 tool steel. Note: Wheel speeds are somewhat higher than the typical 4000 to 7000 fpm (L H Williams, III p 17)

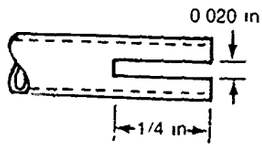
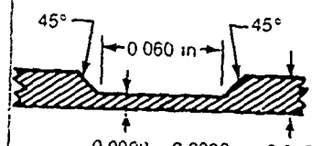
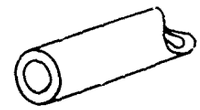
SPECIFIC APPLICATIONS DATA

TABLE 11.3–6 Specific Applications Data for Electrochemical Grinding

Work material	Fully Annealed Low Carbon Steel and Medium Carbon Steel Hardened to 60 R_c	Tungsten Carbide	Stellite Repair Weld on Waspaloy
Workpiece configuration	 Relay frame & armature	 40 blades Face mill cutters	
Wheel type	Al_2O_3	Diamond	Al_2O_3
diameter, in.	14		8
speed, fpm:	6,400	4,000 to 6,000	6,000
Electrolyte type	N Cl	KNO_3	$NaNO_3$
concentration, lb/gal:	0 5	1 0	2 0
Type of cut.	Face	Face	Contour
Depth cut, in	0.030	0 010	0 030 to 0.050
Feed rate, in/min	0.105	3 faces in 80 min	4 0
Voltage, V:	8 to 9		8
Current, A·	1,200	300	125
Wheel contact area, in²	0.25		
Tolerance, finish, benefits and remarks:	Three parts per load 17-second cutting cycle 50 wheel oscillations per minute.	Eliminated rough grinding. One wheel per year in place of several per week. No heat checks—33% more parts per wheel dressing Accuracy was ± 0.00025 incn 30 wheel oscillations per minute	Tolerance was ± 0.0005

11.3 Electrochemical Grinding—ECG

TABLE 11.3-6—Continued

Work material	Inconel Alloy X	High-Nickel Magnetic Lamination	Stainless
Workpiece configuration	 1/8-inch dia 1/64-inch wall tubing		 1 2-inch dia x 0 015-inch thick wall
Wheel type.	Al_2O_3	Al_2O_3	Al_2O_3
diameter. in	5	8	10
speed. fpm:	1,900	6,000	6,000
Electrolyte type:	$NaNO_3$	$NaNO_3$	$NaNO_3 + NaNO_2$
concentration, lb/gal	2.0	2.0	1.7
Type of cut·	Surface	Contour	Surface cutoff
Depth cut. in:	0.25	0.0092	
Feed rate, in/min·	2 0	3.0	3 0
Voltage. √	4	6	8
Current, A:	25	120	25
Wheel contact area, in²			
Tolerance, finish, benefits and remarks	Burr-free and no distortion 120 pieces per hour in place of 100 pieces per day. 0.007-inch radius at bottom of slot Tolerance on width was ± 0 001 inch.	No distortion. No nicks. No wrinkles	No burrs. Less than 0.001-inch runout.

PROCESS SUMMARY

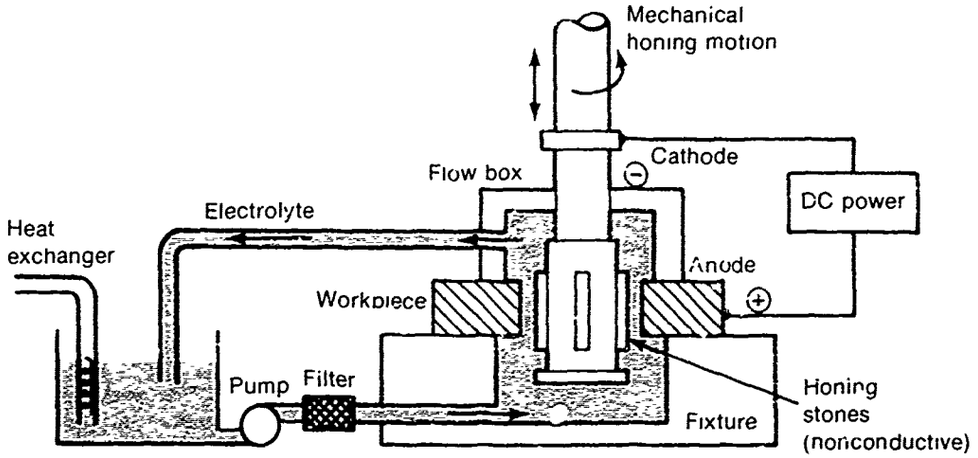


Figure 11.4–1 ECH schematic.

Principles

Electrochemical honing (ECH) is the removal of material by anodic dissolution combined with mechanical abrasion from a rotating and reciprocating abrasive stone (carried on a spindle which is the cathode) separated from the workpiece by a rapidly flowing electrolyte (see figure 11.4-1). The principal material removal action comes from the electrolytic dissolution. The abrasive stones are used to maintain size and to clean the surfaces to expose fresh metal to the electrolytic action. The small electrical gap is maintained by the nonconducting stones which are bonded to the expandable arbor with cement. The cement must be compatible with the electrolyte and the low direct-current voltage. The mechanical honing action uses materials, speeds and pressures typical of conventional honing.

Practical Applications

The advantages of ECH are most pronounced when honing hard metals. The workpiece must be conductive. The absence of heavy mechanical action keeps the workpiece cool and free from heat distortion. The electrolytic action introduces no stresses and deburrs automatically. Blind holes in cast tool steel components and pinion gears of 62 R_c high alloy steels have been honed using ECH.

Operating Parameters

TABLE 11.4–1 Typical Values for ECH Operating Parameters

Power supply	
type:	Direct current
voltage:	6 to 30 V
current:	100 to 3000 A
current density:	100 to 3000 A/in² [15.5 to 465 A/cm²]
Electrolyte	
types and concentrations:	$NaNC_3$, 2 lb/gal [240 g/L] NaCl, 1 lb/gal [120 g/L]
temperature:	100°F [38°C]
pressure:	75 to 150 psi [500 to 1000 kPa]
flow:	Up to 25 gal/min [95 L/min]
gap:	0.003 to 0.010 inch [0.076 to 0.25 mm]

11.4 Electrochemical Honing—ECH

Material Removal Rates and Tolerances

Material is removed 3 to 5 times faster by ECH than by conventional honing and 4 times faster than by internal grinding. Removal of 0.008 inch (0.20 mm) of stock from the bore of 8620 steel in 30 seconds has been reported. Tolerances up to ±0.0001 inch (±0.0025 mm) are possible. Production tolerances achieve ±0.0005 inch (±0.013 mm) on the diameter and 0.0002 inch (0.005 mm) on straightness.

Surface Technology

Surface roughness of 8 to 32 microinches (R_a 0.2 to 0.8 μm) is routine, and roughness of 2 microinches (R_a 0.05 μm) is attainable. For a controlled surface roughness, the stones sometimes are allowed to cut for a few seconds after the current has been turned off. This sequence also will leave a light, compressive residual stress in the surface. For a stress-free surface, the last few seconds of action should be pure electrolytic material removal. This practice is helpful for controlling surface integrity.

Equipment and Tooling

Commercial ECH equipment is made to special engineering order only for internal cylindrical honing. It comes with suitable pumps, tanks, filters, power packs and controls for the combined material removal modes. Automatic size gaging is sometimes incorporated. Tooling for control of the electrolyte flow path and for positioning should be fabricated from stainless steels or plastics that are resistant to the corrosiveness of the electrolyte. Sizes of equipment range from 3/8 inch to 6 inches (10 to 150 mm) in diameter with power packs up to 3000 amperes.

Machining Characteristics

The electrolyte selection and control is not as critical as in ECM because of the cleaning action of the stones.

Hone-Forming

A reversed-polarity version of ECH combines honing with plating. This "hone-forming" process uses plating solutions in place of deplating electrolytes and can achieve rapid, accurate metal deposition. This highly focused plating has achieved deposition rates of 0.0001 inch per minute (0.0025 mm/min) for copper, 0.0005 inch per minute (0.013 mm/min) for nickel and 0.0001 inch per minute (0.0025 mm/min) for chromium. The mechanical (abrasive) honing action prepares a clean surface for the plating and sizes the bores to close tolerances. The equipment is quite similar to ECH equipment, and sometimes the acronym ECF is applied.

PROCESS SUMMARY

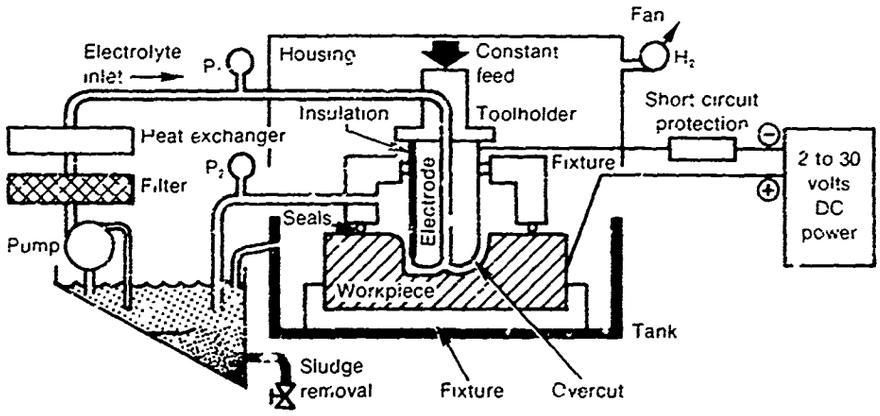


Figure 11.5-1 ECM schematic

Principles

Electrochemical machining (ECM) is the removal of electrically conductive material by anodic dissolution in a *rapidly* flowing electrolyte which separates the workpiece from a shaped electrode (see figure 11.5-1). The filtered electrolyte is pumped under pressure and at controlled temperature to bring a controlled-conductivity fluid into the narrow gap of the cutting area. The shape imposed on the workpiece is nearly a mirror or conjugate image of the shape of the cathodic electrode. The electrode is advanced into the workpiece at a constant feed rate that exactly matches the rate of dissolution of the work material. The current density is the chief factor in setting feed rates and in attaining smoothness. Higher current densities and feed rates create better finishes and higher material removal rates. The hydraulic pressures and tool/workpiece separating forces increase with smaller gaps and can affect workpiece tolerances. Fixtures with epoxies or other securely fastened plastics for insulation locate and control the electrolyte flow so that it is continuous and uniformly turbulent. Materials and design must accommodate the high currents without distortion or overheating. Fixtures must be compatible with the organic salts or acids that are used as electrolytes. Metal dissolved by salt electrolytes forms a sludge of considerable volume, and excess sludge must be removed by filtration, centrifuge or settling. Conductivity control of the electrolyte is maintained by temperature control, usually cooling, and by periodic checks on chemical composition. Both inlet and outlet pressure controls provide flow control. The electrode design must include compensation or correction for the variable current density that comes with variations in the shape of the workpiece and the metal content of the electrolyte. Exact control of all critical parameters is needed to ensure the best results. Cutting action occurs on all exposed faces simultaneously, and there is no mechanical contact or wear of the electrodes. While metal ions are removed from the workpiece surface, hydrogen is generated at the electrode. Adequate provision is required to safely vent this hydrogen.

Practical Applications

ECM is best suited for repetitive production of complex shapes in high strength, hard, or difficult-to-machine materials where high surface quality is needed. The work material must be electrically conductive. Small, odd shaped, difficult or deep holes as small as 1/8-inch (3.2 mm) across can be "drilled" individually or in multiples. Electrodes do not wear; consequently, long tool life is possible. The stress-free material removal eliminates distortion from the ECM operation (but not necessarily from prior stress-inducing operations). Concentration of current density at the edges on the workpiece provides automatic rounding and the absence of burrs. Anodic dissolution generally proceeds independently of material hardness, so finish cuts in the heat-treated state are practical.

The characteristics of an application that make it a prime candidate for ECM are as follows:

- Material is hard or tough.
- Difficult contours are involved.
- Machining without cold working is needed.
- Repetitive production is involved (more than 30 pieces).
- Distortionless, burr-free parts are required.
- High surface quality is required.

11.5 Electrochemical Machining—ECM

Operating Parameters

TABLE 11.5–1 Typical Values for ECM Operating Parameters

Power supply	
type:	Direct current
voltage	5 to 30 V
current:	50 to 40,000 A
Current density:	50 to 3,000 A in²* [8 to 465 A cm²]
Electrolyte	
type and concentration:	
most used	NaCl at 1/2 to 2 lb gal [60 to 240 g L]
frequently used:	$NaNO_3$ at 1 to 4 lb gal [120 to 480 g L]
less frequently used:	Proprietary mixtures
temperature.	90° to 125°F [26° to 46°C]
flow rate:	0.25 gal min 100 A [0.95 L min 100 A]
velocity:	5,000 to 10,000 fpm [1,500 to 3,000 m min]
inlet pressure.	20 to 300 psi [137 to 2,060 kPa]
outlet pressure:	0 to 45 psi [0 to 310 kPa]
Frontal working gap	0.003 to 0.030 inch [0.076 to 0.76 mm]
Side overcut:	0.005 to 0.040 inch [0.127 to 1 mm]
Feed rate.	0.020 to 0.50 in min [0.51 to 13 mm min]
Electrode material:	Brass, copper, bronze (table 11.5–1C)
Tolerance	
2-dimensional shapes:	± 0.001 inch [± 0.025 mm]
3-dimensional shapes:	± 0.002 inch [± 0.051 mm]
Surface roughness, R_a,	
frontal.	8 to 63 microinches [0.2 to 1.6 μm]

*Limited by overtemperature in workpiece or electrolyte

Material Removal Rates and Tolerances

Material removal rate is independent of material hardness and for most common metals is approximately 0.10 cubic inch per minute [1.64 cm³/min] per 1000 amperes. The cutting occurs simultaneously on all exposed surfaces, and this aids productivity. Accuracy up to ± 0.004 inch [± 0.1 mm] is usual for contoured cavities, and accuracy up to ± 0.0010 inch [± 0.025 mm] is common for frontal cuts or cuts made with refined tools. These tolerances can be cut in half with well-developed tools and experienced operators.) Deep cavities will have a taper of up to 0.001 inch per inch [0.001 mm/mm] with 0.007 inch [0.13 mm] overcut gap unless a special tool design is used. Internal radii of 0.007 inch [0.18 mm] and external radii of 0.002 inch [0.051 mm] are attainable. Tolerance capabilities are dependent upon part geometry, tool design, and particular shop practices and require careful checking with experienced people for particular applications.

Surface Technology

Surfaces roughness of 10 to 32 microinches R_a [0.4 to 0.8 μm] is normal. Roughness values decrease with the increase in cutting rates that accompanies higher current densities. The faster the cutting, the better the finish. Mirror finishes (8 microinches R_a [0.2 μm] or better) are easily obtained in frontal cuts of stainless steels or nickel alloys. The side-gap areas generally are much rougher because current density is lower in these areas. Incorrect electrolyte, different work material heat treatment, low current density, or stray current can produce selective etching pits or intergranular attack at the grain boundaries. The absence of residual stress (in contrast with the presence of compressive stresses from many mechanical processes) produces a reduced high cycle fatigue strength (by comparison), but these values more nearly represent the true or unaffected material values. Any physical blemish in the tool will be reproduced on the workpiece, and poor flow conditions can produce striations in the surface. Hydrogen embrittlement is not a problem because the hydrogen is liberated at the electrode (as a gas) and is carried away by the flowing electrolyte as shown in figure 11.5–2.

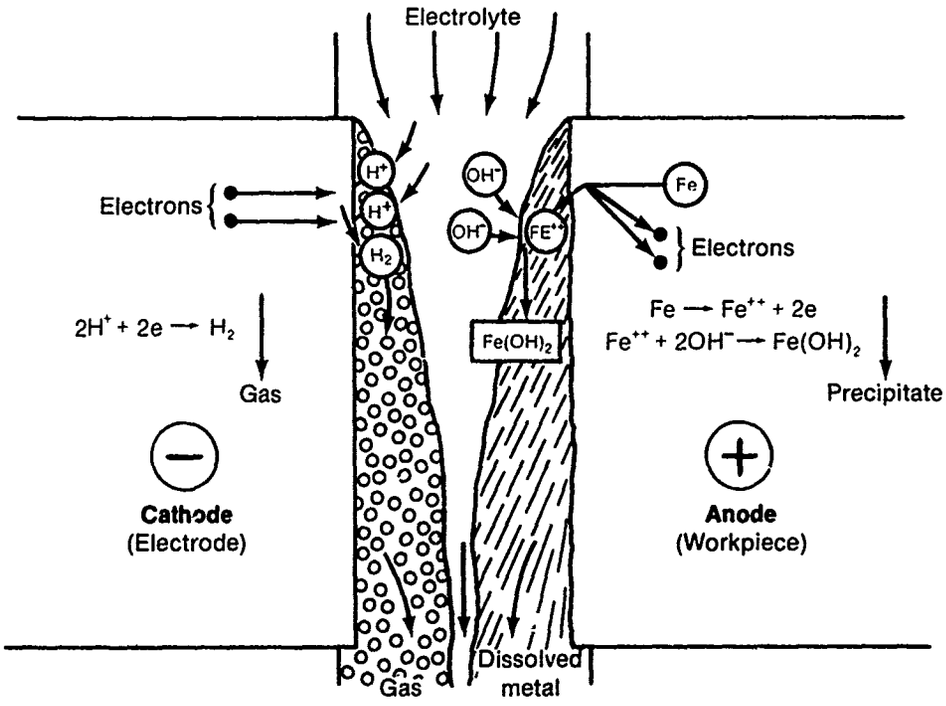


Figure 11.5–2 Electrochemical reactions in the working gap during ECM.

Equipment and Tooling

The available equipment ranges from small 50-ampere bench models to 40,000-ampere models with a five-foot-cube working space. Power sources providing from 4 to 30 volts direct current are available with special, fast-acting, short-circuit protective devices. Ancillary equipment, such as pumps, tanks, plastic piping, mixing vats and sludge-disposal devices, should be engineered as a complete system. Equipment and tools should be rigid enough to withstand the forces from the high hydraulic pressures. The fixtures, the insulation and the tool material must be chemically compatible with the electrolyte. Electrode materials are high-conductivity coppers, brasses or bronzes (see table 11.5-10).

Tooling trials and start-up costs should be carefully assessed and included in development plans. The electrode design and correction during tryout may require several "cut and try" cycles for complex shapes. Filtration of the electrolyte to the 7.5-micrometer level or better is most desirable. Placement of the filter immediately ahead of the electrode is good practice. With salt solutions, the volume of metal hydroxide or metal hydrate can be 100 to 500 times the volume of the metal removed, as noted in table 11.5-13. Settling or filtration for removal of these "chips" is necessary, and disposal requires environmentally satisfactory planning.

Machining Characteristics

Process control and the sequence of operating steps must be exact and precisely repetitive for good production. The workpiece should be thoroughly cleaned and/or oiled after ECM to prevent corrosion. Periodic washdown of the equipment can reduce maintenance expenses. Special safety precautions should be instituted when the electrolyte used is a chlorate or a nitrite (see table 11.5-6).

11.5 Electrochemical Machining—ECM

SELECTED DATA

There are several valid techniques for selecting operating parameters for ECM. The steps in table 11.5-2 are recommended as one logical sequence. Supporting data come from the other figures and tables in accordance with the terms as explained in figure 11.5-3.

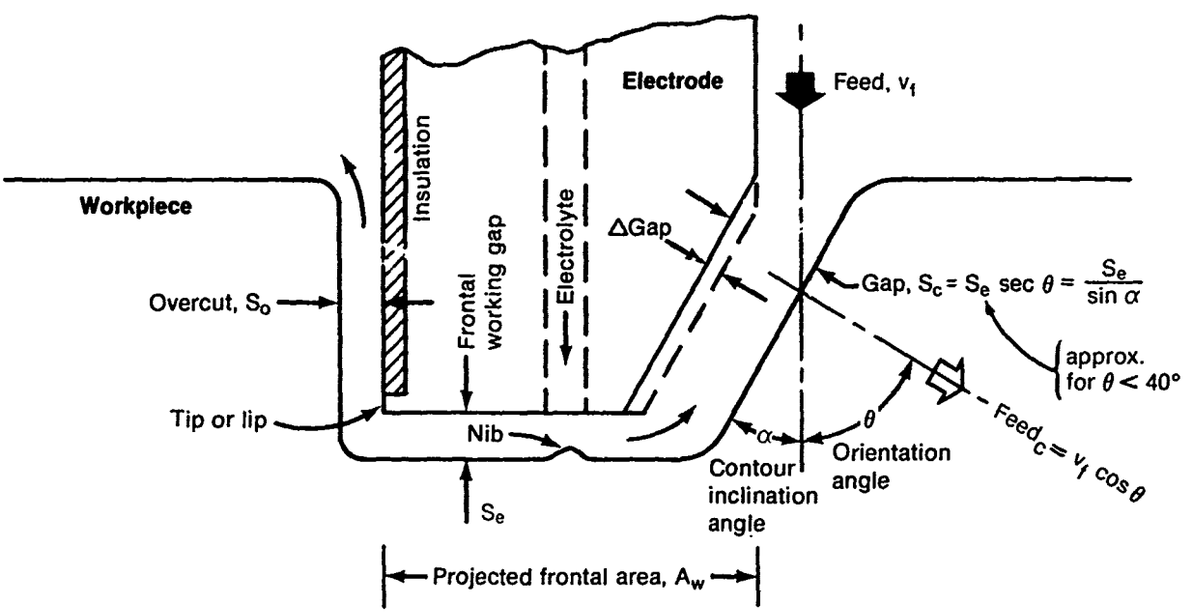


Figure 11.5-3 ECM parameter terminology.

TABLE 11.5–2 Steps To Select ECM Operating Parameters

ITEM	DATA
1. Workpiece material	From engineering drawings obtain material type, composition, and metallurgical state. Must be electrically conductive material.
2. Material removal rate, MRR, (at 100% efficiency)	A. For planning or rough estimating, good approximation can be had from the following values which apply to most common conductive materials and alloys: 0.1 in^3/min/1,000 A [1.64 cm^3/min/1,000 A] 1.0 in^3/min/10,000 A [16.4 cm^3/min/10,000 A] B. For pure metals, removal rate depends on valence and the relationships established in Faraday's second law: $\text{specific removal rate} = \frac{\text{atomic weight}}{\text{valence}} \times \frac{1}{\text{density}} \times \frac{1}{96{,}494}$ where 96,494 is Faraday's constant representing the number of coulombs (or ampere-seconds) of electricity required to remove one gram equivalent weight of material. Gram equivalent weight is atomic weight divided by valence. Values in table 11.5–3 represent theoretical metal removal rates assuming 100% current efficiency (all current goes to dissolving metal and none goes to gas generation at the anode). C. For alloys, rates of material removal can be calculated from alloy chemical composition using Faraday's law (table 11.5–4).
3. Assume efficiency, h, of electrochemical action	With complex tools, long electrolytic path, higher voltage or current density, valence variation or chemical activity, and appreciable stray current or spray, the efficiency can decline to 80 to 90%. For most estimating prior to a pilot run, 90% is a fair assumption.
4. Determine projected area, A_w, of electrode perpendicular to feed direction	See figure 11.5–3
5. Determine maximum current density available	Rated amperes of equipment ÷ A_w
6. Establish feed rate, v_f, that exactly matches rate of material dissolution. Current density and feed rate will be in balance.	A. $\frac{\text{material removal rate}}{\text{projected area}} = \frac{\text{MRR times h}}{A_w} = v_f$ B. See figure 11.5–7 and 11.5–8 for quick approximations. (Figure 11.5–9 for one specific alloy-electrolyte combination.) C. The current density that balances the feed rate is limited by (1) boiling of the electrolyte, see table 11.5–7, (2) overtemperature in the workpiece from resistive heating (and possible distortion or dimensional inaccuracies), or (3) available power supply (item 5). See also table 11.5–9.
7. Electrolyte Selection Composition Concentration Temperature	Table 11.5–5 and 11.5–6. Many applications try simple NaCl first, then try more complex electrolytes only if necessary. Keep concentrations as low as compatible with productivity so as to reduce accumulations of salt deposits on equipment and tooling. Selection should be based upon compatibility with particular metallurgical state of alloy being machined, feed rate, surface roughness (both frontal and side) and surface integrity.* Temperature control should be within ±1°F [±1.8°C] to attain consistent electrolyte conductivity at the inlet to the electrode, see table 11.5–7, figures 11.5–14 and 11.5–15.
8. Electrolyte Testing Select a measure for electrolyte condition or control Specific Gravity Salimeter Conductivity Titration	 Nomographs, figures 11.5–10 to 11.5–12. Table 11.5–8, figure 11.5–13. Figures 11.5–14 and 11.5–15. Standard analytic chemical test.

*For detail on interrelationships, see J. A. Cross, ECM machinability data, Technical paper MR73-228, Society of Manufacturing Engineers, Dearborn, MI, 1973, or J. A. Cross and A. U. Jollis, Electrochemical machining (ECM), Technical report AFML-TR-72-188, General Electric Company, 1972.

TABLE 11.5-2—Continued

ITEM	DATA
9. Voltage	A minimum voltage, ΔE, is required to initiate full electrochemical action, see figure 11.5-17 and table 11.5-9. The usual operating range is between 5 and 30 volts. The value is set to attain the desired current density that matches the feed rate. Typical setting ranges are: Steel alloys 5 to 10 volts dc High strength alloys 10 to 20 Titanium alloys 15 to 25 Superalloys 10 to 25
10. Tool design, cutting gaps and corrections Frontal gap, S_f Side gap, S_c Orientation, Δ gap	The equilibrium frontal gap is a compromise depending on tool design and prior parameter selections, see figures 11.5-16 and 11.5-17. It is not independently adjustable. Electrode shape should be adjusted depending on orientation angle, see figure 11.5-18.
11. Current	Cannot be set independently—it is a result of equilibrium among prior parameters to just balance feed rate and MRR. Adjusted by setting feed rate. Note that current increases as starting gap reaches operating or equilibrium gap during full engagement when selected current density (item 6) is attained.
12. Electrolyte Pressures	The tool design and operating gaps will determine pressures required to get rapid turbulent flow. Inlet pressures range from 20 to 300 psi. Outlet pressures range from 0 to 45 psi (and sometimes to 75). Adequate provision to contain the considerable hydraulic forces is needed in the plumbing, fixtures, electrodes and machine if good accuracy is to be attained (figure 11.5-19).
13. Starting Gap and Depth of Feed	These parameters can be set independently and are a function of the shape to be generated and the shape of the raw material stock. Adequate cutting stock is required to permit penetration of electrode to point of electrochemical equilibrium.
14. Tool Construction	The insulation and tool materials must be compatible with the electrolyte being used. Typical materials are listed on tables 11.5-10 to 11.5-12.
15. Sludge	The "chips" from ECM are in the form of a sludge in the electrolyte composed of metal hydroxides or hydrates. The volume of sludge is considerable with salt electrolytes, see table 11.5-13.
16. Trial cut	The extensive interrelations among the ECM parameters make a trial cut highly desirable. If it is performed on a sample of the workpiece in the metallurgical state equal to the production item, a simple metallographic section of the ECM surface can reveal possible surface integrity imperfections.

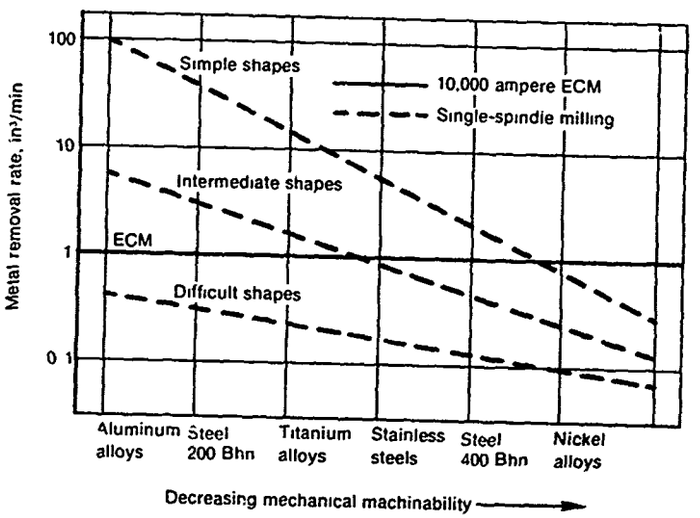


Figure 11.5–4 Comparison of metal removal rates for 10,000 ampere ECM and single-spindle NC conventional milling of equal investment cost. (Courtesy of Lockheed-Burbank)

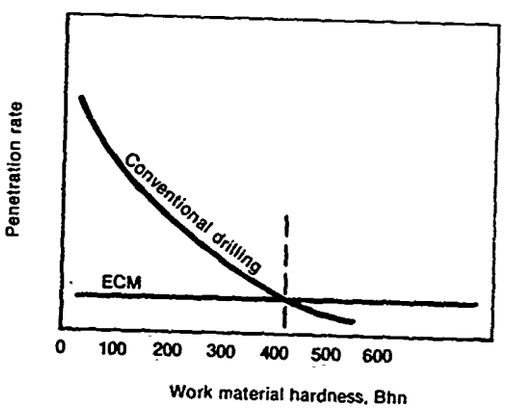


Figure 11.5–5 Relative penetration rates of ECM and conventional drilling for increasing work material hardness. (Courtesy of Cincinnati Milacron)

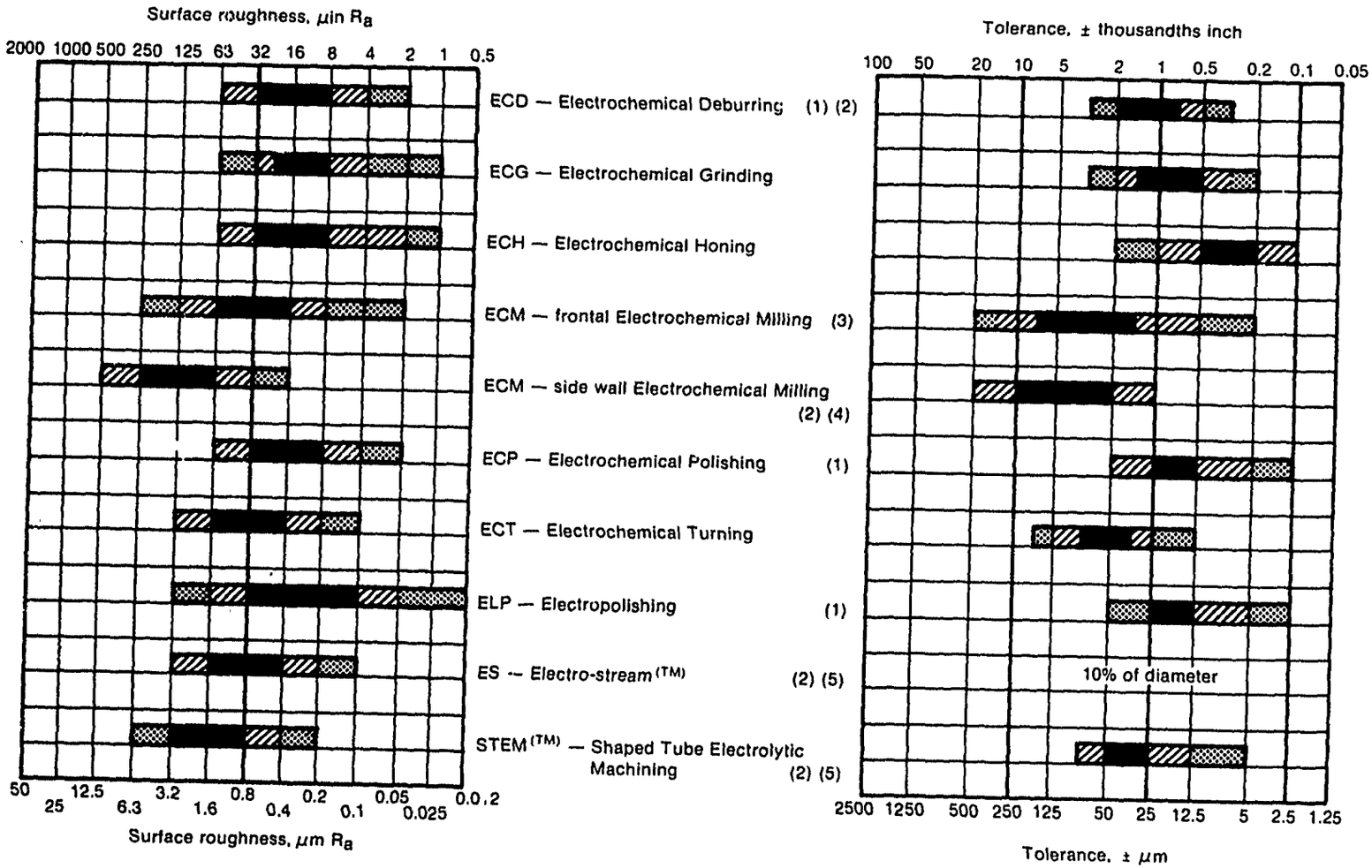


Figure 11.5-6 Typical surface roughness values and typical tolerances from various forms of electrolytic machining.

TABLE 11.5–3 Material Removal Rates for ECM of Pure Metals Assuming 100 Percent Current Efficiency

METAL	ATOMIC WEIGHT	VALENCE	DENSITY		REMOVAL RATES AT 1000 AMPERES			
	g		lb/in³	g/cm³	lb/hr	in³/min	g/min	cm³/min
Aluminum	26.98	3	0.098	2.71	0.74	0.126	5.59	2.06
Antimony	121.75	3 5	0.239	6.62	3.33 2.00	0.23 0.14	25.17 15.12	3.77 2.30
Arsenic	74.92	3 5	0.207	5.73	2.05 1.23	0.17 0.10	15.50 9.30	2.79 1.64
Beryllium	9.012	2	0.067	1.86	0.37	0.092	2.80	1.5
Bismuth	208.98	3 5	0.354	9.80	5.73 3.44	0.27 0.16	43.32 26.01	4.43 2.62
Cadmium	112.40	2	0.313	8.67	4.62	0.25	34.93	4.1
Chromium	51.896	2 3 6	0.260	7.20	2.14 1.43 0.71	0.137 0.092 0.046	16.18 10.81 5.37	2.25 1.51 0.75
Cobalt	58.93	2 3	0.322	8.92	2.42 1.62	0.125 0.084	18.30 12.25	2.05 1.38
Columbium (Niobium)	92.906	3 4 5	0.310	8.58	2.55 1.92 1.53	0.132 0.103 0.08	19.28 14.52 11.57	2.18 1.66 1.34
Copper	63.546	1 2	0.324	8.97	5.22 2.61	0.268 0.134	39.46 19.73	4.39 2.29
Germanium	72.59	4	0.192	5.32	1.49	0.13	11.26	2.13
Gold	196.967	1 3	0.698	19.33	16.22 5.40	0.39 0.13	122.62 40.82	6.46 2.13
Hafnium	178.49	4	0.473	13.10	3.68	0.13	27.82	2.13
Indium	114.82	1 2 3	0.264	7.31	9.43 4.71 3.14	0.60 0.30 0.20	71.28 35.61 23.74	9.84 4.92 3.28
Iridium	192.20	3 4	0.813	22.52	5.27 3.96	0.11 0.08	39.84 29.94	1.66 1.24
Iron	55.847	2 3	0.284	7.86	2.30 1.53	0.14 0.09	17.39 11.57	2.21 1.47
Lead	207.19	2 4	0.410	11.36	8.52 4.26	0.35 0.17	64.41 32.21	5.76 2.79
Magnesium	24.312	2	0.063	1.75	1.00	0.27	7.56	4.48
Manganese	54.938	2 3 4 6 7	0.270	7.48	2.26 1.50 1.13 0.75 0.65	0.14 0.09 0.07 0.05 0.04	17.09 11.39 8.54 5.69 4.91	2.29 1.49 1.12 0.75 0.64
Molybdenum	95.94	3 4 6	0.369	10.22	2.63 1.97 1.32	0.12 0.09 0.06	19.89 14.92 9.95	1.96 1.47 0.98
Nickel	58.71	2 3	0.322	8.90	2.41 1.61	0.13 0.08	18.21 12.17	2.03 1.36
Osmium	109.20	2 3 4 8	0.815	22.57	7.82 5.22 3.91 1.95	0.16 0.10 0.08 0.04	59.12 39.47 29.56 14.78	3.24 2.16 1.62 0.81

TABLE 11.5-3—Continued

METAL	ATOMIC WEIGHT	VALENCE	DENSITY		REMOVAL RATES AT 1000 AMPERES			
	g		lb/in³	g/cm³	lb/hr	in³/min	g/min	cm³/min
Palladium	106.40	2 4 6	0.434	12.02	4.38 2.19 1.46	0.17 0.08 0.06	33.11 16.56 11.04	2.79 1.31 0.98
Platinum	195.09	2 4	0.775	21.47	8.02 4.01	0.17 0.09	60.63 30.32	2.79 1.47
Rhenium	186.20	3 4 5 6 7	0.756	20.94	7.60 3.82 3.07 2.55 2.19	0.17 0.08 0.07 0.06 0.05	57.46 28.88 23.21 19.28 16.56	2.79 1.31 1.15 0.98 0.82
Rhodium	102.905	3	0.447	12.38	2.82	0.11	21.32	1.80
Silver	107.868	1	0.379	10.50	8.87	0.39	67.06	6.36
Tantalum	180.948	5	0.600	16.62	2.98	0.08	22.53	1.31
Thalium	204.37	1 3	0.428	11.86	16.80 5.60	0.65 0.22	127.01 42.34	10.46 3.61
Thorium	232.038	4	0.421	11.66	4.76	0.19	35.99	3.12
Tin	118.69	2 4	0.264	7.31	4.88 2.44	0.31 0.15	36.88 18.44	5.08 2.54
Titanium	47.90	3 4	0.163	4.52	1.31 0.99	0.13 0.10	9.90 7.48	2.18 1.65
Tungsten	183.85	6 8	0.697	19.31	2.52 1.89	0.06 0.05	19.05 14.28	0.98 0.74
Uranium	238.03	4 6	0.689	19.08	4.90 3.27	0.12 0.08	37.04 24.69	1.83 1.22
Vanadium	50.942	3 5	0.220	6.09	1.40 0.84	0.11 0.06	10.58 6.35	1.74 1.04
Zinc	65.37	2	0.258	7.15	2.69	0.17	20.34	2.78
Zirconium	91.22	4	0.234	6.48	1.87	0.13	14.14	2.19

TABLE 11.5-4 Material Removal Rates for ECM of Alloys Assuming 100 Percent Current Efficiency

ALLOY	THEORETICAL REMOVAL RATES FOR 1,000 AMPERES PER SQUARE INCH	
	in³/min	
4340 steel	0.133	
17-4 PH	0.123	
A-286	0.117	
M252	0.110	
Rene 41	0.108	
Udimet 500	0.110	
Udimet 700	0.108	
L605	0.107	

NOTE: Rates listed were calculated using Faraday's law and valences as follows:

Aluminum	3	Copper	2	Silicon	0
Carbon	0	Iron	2	Titanium	4
Columbium	3	Manganese	3	Tungsten	6
Cobalt	2	Molybdenum	4	Vanadium	5
Chromium	3	Nickel	2		

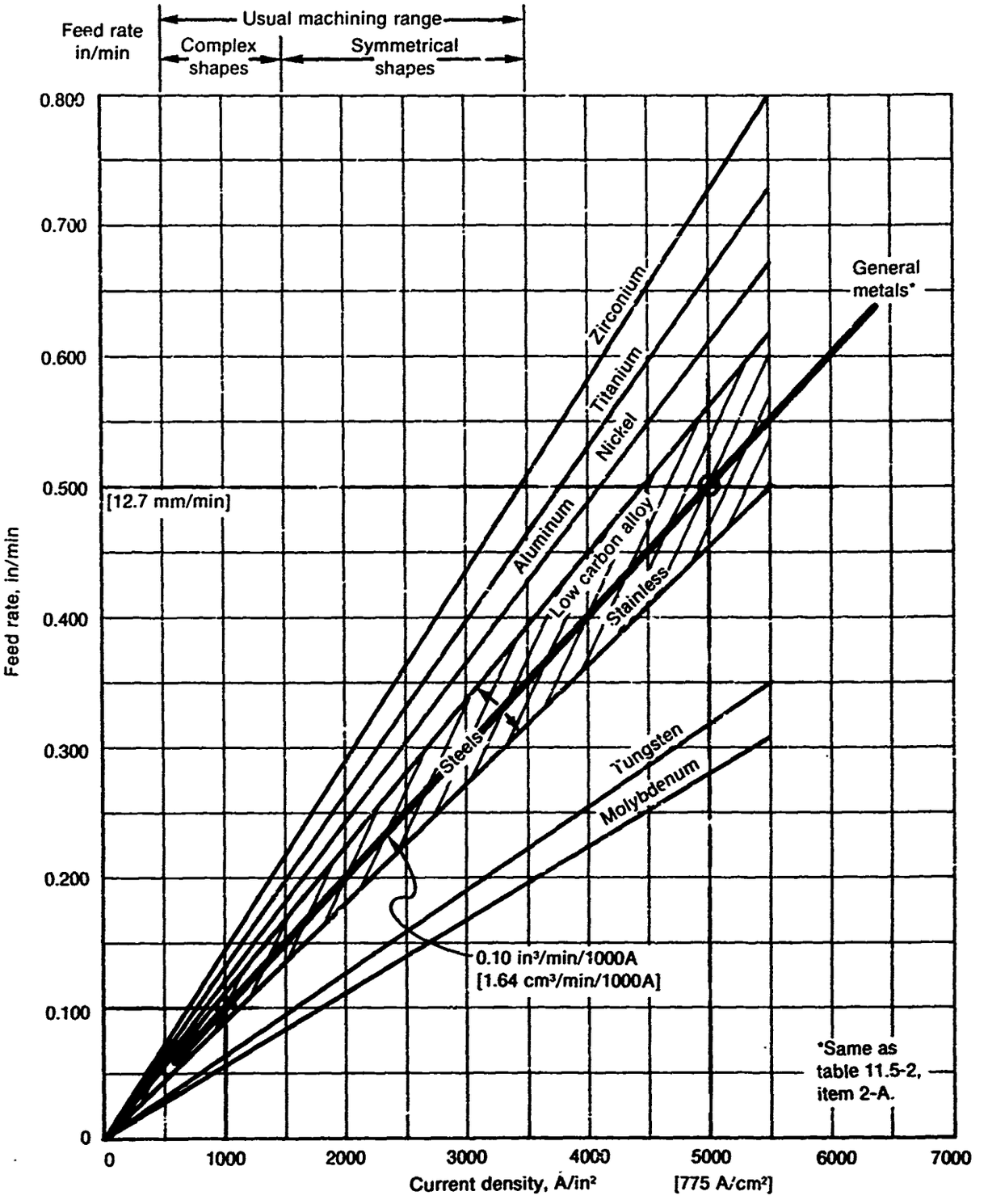


Figure 11.5–7 Feed rates versus current density for ECM of various materials. (Courtesy of Cincinnati Milacron)

11.5 Electrochemical Machining—ECM

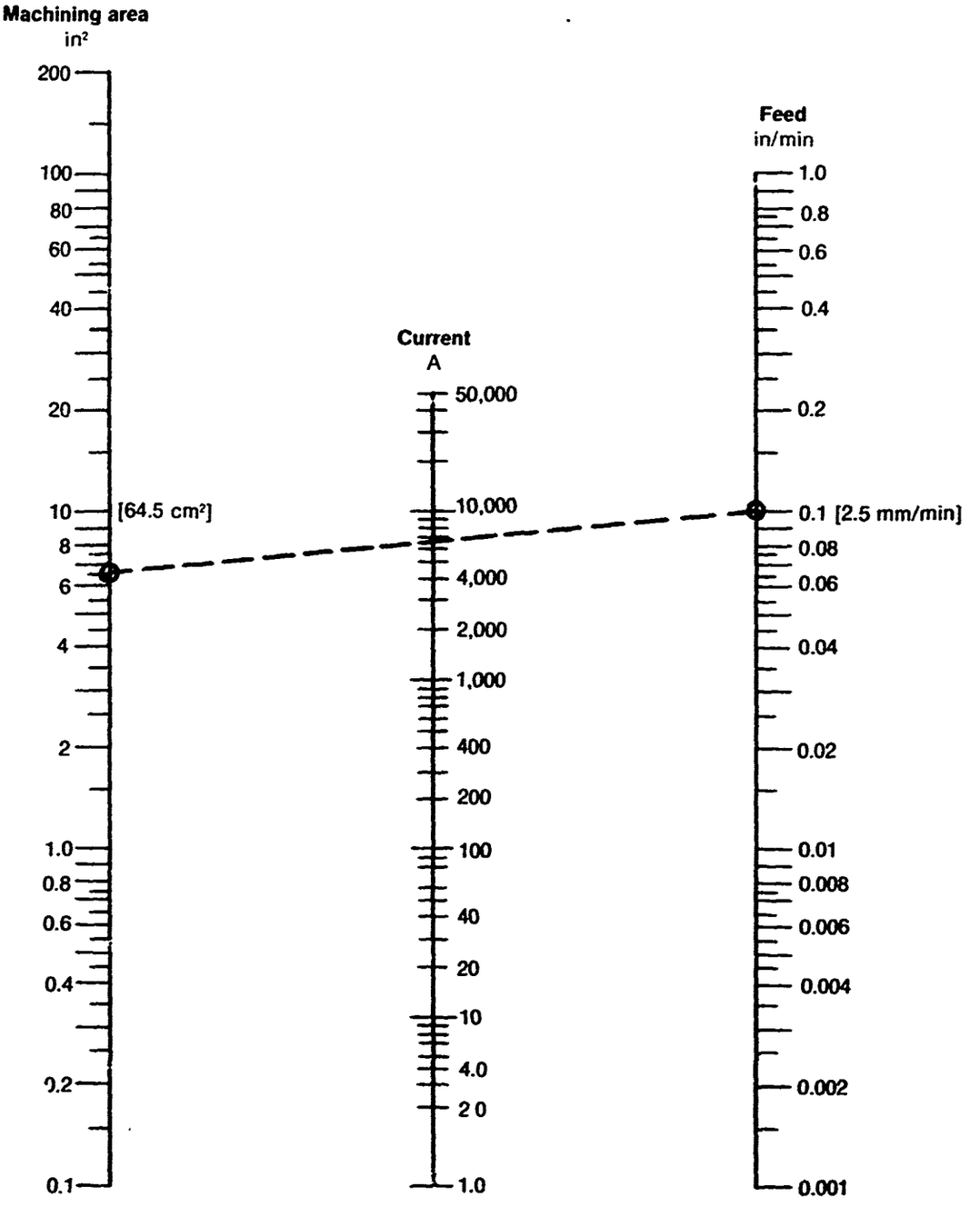


Figure 11.5–8 Nomogram for approximating ECM feed rates and currents. (Courtesy of Anocut Inc.)

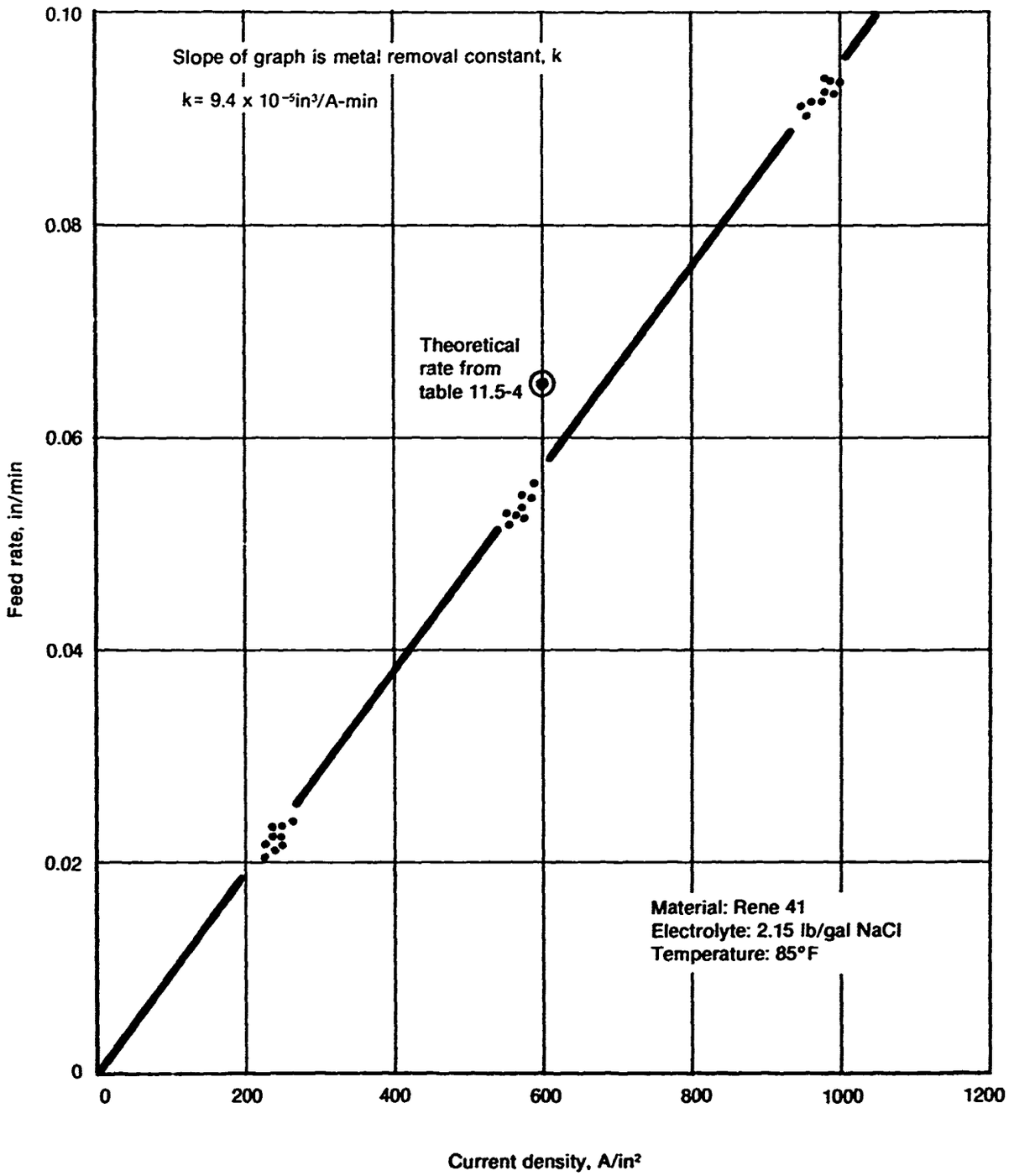


Figure 11.5–9 Typical material removal rate data for a specific alloy-electrolyte combination with data points from ECM machinability data test rig. (G. Bellows, ECM machinability data and ratings, Technical paper MR67-710, Society of Manufacturing Engineers, Dearborn, MI, 1967)

TABLE 11.5-5 Electrolyte Selection Guide

WORK MATERIAL*	ELECTROLYTE						REMARKS
	Composition†	Concentration‡		Temperature at inlet			
		lb/gal	g/L	°F	°C		
ALUMINUM & ALUMINUM ALLOYS	NaCl	up to 1	120	90 to 125	32 to 52		Generally better finishes.
	$NaNO_3$	up to 2	240	90 to 125	32 to 52		
2024-T4	$NaNO_3$	1.25	150	100	38		
7075	NaCl + $NaNO_3$	0.9 + 0.2	108 + 24	100	38		
BERYLLIUM	$NaNO_3$	4	480	100	38		
COBALT ALLOYS	NaCl	up to 2	240	90 to 125	32 to 52		
MAR-M509	NaCl	1.0	120	100	38		
HS-21	NaCl + $NaNO_3$	2 + 0.25	240 + 30	100	38		
Haynes alloy 25 (L605)							
HS-31 (X-40)	NaCl + NaF	0.25 + 0.02	30 + 2.4	100	38		
COLUMBIUM ALLOYS	—	—	—	—	—		Difficult to ECM. Special electrolytes and special flow control tooling required.
COPPER & COPPER ALLOYS	$NaNO_3$	up to 4	480	90 to 125	32 to 52		Generally better finishes.
	NaCl	up to 2	240	90 to 125	32 to 52		
IRON BASE ALLOYS	NaCl	up to 2.5	300	90 to 125	32 to 52		$NaClO_3$ for specialized applications.
Low carbon steels							
1018	NaCl	0.25	30	100	38		
Medium carbon steels							
4130	NaCl	1	120	100	38		
5160	NaCl	0.4 to 1.0	48 to 120	90	32		
High strength steels							
Grade 250 maraging	NaCl	1.25 (0.25 to 1.75)	150 (30 to 210)	110	43		
300M	NaCl or	1	120	100	38		
	NaCl + $NaNO_3$	1 + 2	120 + 240	100	38		
4340	NaCl or	0.9 to 1.0	108 to 120	95 to 100	35 to 38		
	NaCl + $NaNO_3$	1 + 0.5	120 + 60	100	38		Also 1.8 to 1.0 lb/gal $NaNO_3$.
A-286	$NaNO_3$	2.0	240	100	38		
D6ac	NaCl	1.5	180	90	32		

*Caution: Particular metallurgical state must be known because IGA, excessive pitting, or excessive roughness can occur with some heat-treat states. A metallographic check on ECM'd test specimen is recommended.

†For safety and corrosiveness, see table 11.5-6. There are many proprietary mixtures or additives to the base composition that have desirable effects on finish, corrosiveness and sometimes feed rates. These should be explored through regular vendors or ECM operators.

‡A wide range of concentrations (and compositions) will permit ECM to continue, so the final selection will depend on a balanced relationship among all factors. The lower concentrations will reduce the salt deposits on equipment and tools. Note that about 80 percent of applications circa 1979 use NaCl (in various concentrations), 18 percent use $NaNO_3$, and all others comprise only 2 percent of total.

TABLE 11.5-5—Continued

WORK MATERIAL*	ELECTROLYTE					REMARKS
	Composition†	Concentration‡		Temperature at Inlet		
		lb/gal	g/L	°F	°C	
Tool steels						
M50	$NaClO_3$§	2	240	90	32	
L6	$NaClO_3$§	3.75	450	86	25	
D2	NaCl	1.0	120	100	38	
Carpenter 20	NaCl	0.67	80	85	25	
Stainless steels						
Austenitic						
302	NaCl + NaF	0.25 + 0.02	30 + 2.4	100	38	Wrought alloys with nonconductive inclusion can yield erratic results.
303	NaCl + $NaNO_3$	1.0 + 0.17	120 + 20	70	21	
316	NaCl	1	120	100	38	
Martensitic						
410	NaCl or	0.8	96	80	27	
	NaCl + $NaNO_3$	1.6 + 0.2	192 + 24	115	46	
Precipitation hardening						
17-4 PH	NaCl or	0.8 to 1	96 to 120	80	26	
	$NaNO_3$	2 (0.25 to 4)	240 (30 to 480)	100	38	
Gray cast iron	NaCl	up to 2.5	300	90 to 125	32 to 52	Feed rates limited by size of graphite particles.
12% Cr white cast iron	$NaNO_3$ or	up to 4	480	90 to 125	32 to 52	Rougher finishes.
	NaCl	1.2	144	120	49	
MOLYBDENUM ALLOYS	NaOH	up to 1.5	180	100	38	Electrolyte becomes acid with use. NaOH may be added to maintain pH.
TZM	NaCl	1	120	95	35	
NONMETALLICS B_4C, ZrC, TiB_2, ZrB_2	NaCl	up to 2.5	300	100	38	
NICKEL BASE ALLOYS	NaCl or	up to 2.5	300	100	38	Side walls and low current density areas subject to IGA and/or rough finishes.
	$NaNO_3$	up to 4	480	100	38	

*Caution: Particular metallurgical state must be known because IGA, excessive pitting, or excessive roughness can occur with some heat-treat status. A metallographic check on ECM'd test specimen is recommended.

†For safety and corrosiveness, see table 11.5-6. There are many proprietary mixtures or additives to the base composition that have desirable effects on finish, corrosiveness and sometimes feed rates. These should be explored through regular vendors or ECM operators.

‡A wide range of concentrations (and compositions) will permit ECM to continue, so the final selection will depend on a balanced relationship among all factors. The lower concentrations will reduce the salt deposits on equipment and tools Note that about 80 percent of applications circa 1979 use NaCl (in various concentrations), 18 percent use $NaNO_3$, and all others comprise only 2 percent of total.

§See precautions, table 11.5-6

TABLE 11.5–5—Continued

WORK MATERIAL*	ELECTROLYTE					REMARKS
	Composition†	Concentration‡		Temperature at Inlet		
		lb/gal	g/L	°F	°C	
Wrought						
M252	NaCl	2	[illegible]	105	41	ST (not aged condition) gives better results.
Waspaloy	NaCl	1	[illegible]	95	35	
Hastelloy alloy X	NaCl	2	[illegible]	75	24	
Astroloy	$NaNO_3$ or	1 to 2	[illegible]	100	38	Cuts easily and rapidly.
	NaCl + NaF	0.75 + 0.25	[illegible]	100	38	
Inconel alloy 700	NaCl	1	[illegible]	100	38	
Inconel 706	NaCl	0.8	[illegible]	75	24	
Inconel 718	NaCl or	0.9 to 1.0	[illegible]	95 to 100	35 to 38	Better results in solution treated and aged condition.
	$NaNO_3$	1.8 to 2.0	[illegible]	95 to 100	35 to 38	
Rene 41	NaCl	2.15 (or 1.0)	[illegible]	75 (or 95)	24 (or 35)	
Udimet 500	NaCl	1	[illegible]	100	38	
Udimet 700	NaCl	1	[illegible]	100	38	
Inconel alloy X	NaCl + $NaNO_3$	2 + 0.5	[illegible]	100	38	
Cast						
IN-100	NaCl	1	[illegible]	100	38	
Rene 80	NaCl	1	[illegible]	100	38	
Rene 125	NaCl	1	[illegible]	100	38	
AF2-1DA	$NaNO_3$	2	[illegible]	100	38	
Rene 95	$NaNO_3$ or	1.8 to 2.0	[illegible]	95 to 100	35 to 38	
	NaCl	1.0	[illegible]	100	38	
TANTALUM	—	—	—	—	—	Difficult to ECM. Special electrolytes and flow controlled tooling required.
TITANIUM ALLOYS	NaCl	up to 1.5	[illegible]	95 to 105	35 to 41	Use voltages greater than 12.
Commercially pure	—	—	—	—	—	Not recommended. Forms inhibiting films. Try ECG.
Alpha alloys						
Ti-5Al-2.5Sn (A110)	NaCl	0.9 to 1.0	[illegible]	95 to 100	35 to 38	
Ti-6Al-2Sn-4Zr-2Mo	NaCl or	1	[illegible]	90	32	
	NaCl + NaF	3/4 + 0.01	[illegible]	100	38	
Alpha-beta alloys						
Ti-6Al-4V	NaCl	1 (0.25 to 1.75)	[illegible]	100	38	
Ti-8Al-1Mo-1V	NaCl	0.8	[illegible]	105	41	
Ti-6Al-6V-2Sn	NaCl	1 (0.25 to 1.75)	[illegible]	100	38	3:1 mixture NaCl:$NaNO_3$ up to 1.0 lb/gal. Proprietary additives helpful to reduce film formation.

*Caution: Particular metallurgical state must be known because IGA, excessive pitting, or excessive roughness can occur with some heat-treat states. A metallographic check on ECM'd test specimen is recommended.

†For safety and corrosiveness, see table 11.5–6. There are many proprietary mixtures or additives to the base composition that have desirable effects on finish, corrosiveness and sometimes feed rates. These should be explored through regular vendors or ECM

‡A wide range of concentrations (and compositions) will permit ECM to continue, so the final selection will depend on a balanced relationship among all factors. The lower concentrations will reduce the salt deposits on equipment and tools. Note that about 80 percent of applications circa 1979 use NaCl (in various concentrations), 16 percent use $NaNO_3$, and all others comprise only 2 percent of total.

TABLE 11.5–5—Continued

WORK MATERIAL*	ELECTROLYTE					REMARKS
	Composition†	Concentration‡		Temperature at Inlet		
		lb/gal	g/L	°F	°C	
TUNGSTEN	NaOH NaOH	0.25 to 1.5 2	30 to 180 240	100 75	38 24	Must constantly be replenished. (Personnel hazard and hard on pumps as nonlubricating.)
URANIUM	NaCl	up to 2	240	100	38	
ZINC ALLOYS	NaCl	up to 2	240	100	38	
ZIRCONIUM	NaCl	up to 2	240	100	38	

*Caution: Particular metallurgical state must be known because IGA, excessive pitting, or excessive roughness can occur with some heat-treat states. A metallographic check on ECM'd test specimen is recommended.

†For safety and corrosiveness, see table 11.5–6. There are many proprietary mixtures or additives to the base composition that have desirable effects on finish, corrosiveness and sometimes feed rates. These should be explored through regular vendors or ECM operators.

‡A wide range of concentrations (and compositions) will permit ECM to continue, so the final selection will depend on a balanced relationship among all factors. The lower concentrations will reduce the salt deposits on equipment and tools Note that about 80 percent of applications circa 1979 use NaCl (in various concentrations), 18 percent use $NaNO_3$, and all others comprise only 2 percent of total.

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TABLE 11.5–6 Corrosiveness and Safety Considerations for ECM Electrolytes

ELECTROLYTE	COST RATIO*	SAFETY	CORROSIVENESS
Sodium chloride (NaCl)	1.0	Safe.	Highly corrosive. Brass or stainless steel required for tooling.
Sodium nitrate ($NaNO_3$)	3.0†	Safe in solution; moderate fire hazard when dry and mixed with organic materials.	Noncorrosive—mild steel can be used for tooling.
Sodium chlorate ($NaClO_3$)	7.5	Safe in solution; very highly combustible when dry. Special precautions required.	Noncorrosive.
Sodium hydroxide (NaOH)	2.0	Caution—will cause severe burns.	Mildly corrosive on ferrous alloys and more corrosive on aluminum, zinc and cadmium.
Sodium fluoride (NaF)	8.0	Poisonous and needs check of medical hazards.	Highly corrosive.
Potassium chloride (KCl)	2.3	Safe.	Highly corrosive.
Sodium nitrite ($NaNO_2$)	6.7	Similar to $NaNO_3$, but less stable. Special fire precautions advised.	Noncorrosive.
Sodium sulphate ($NaSO_4$)	3.0	Safe.	Highly corrosive.
Potassium nitrate (KNO_3)	8.0	Similar to $NaNO_3$, but less stable.	Noncorrosive.

*Based on salt as 1.0 and market circa 1972.

†As it takes twice as much $NaNO_3$ for conductivity equivalent to NaCl, the cost ratio for equal conductivity is 1:6. Similar factors affect other electrolytes.

TABLE 11.5–7 Boiling Point of Water at Various Pressures

GAUGE PRESSURE		ABSOLUTE PRESSURE	BOILING TEMPERATURE
in Hg		in Hg	°F
29.5		0.5	58.8
29.0		1.0	79.0
20.0		10	161.5
10.0		20	192.4
psi		psi	
0		14.7	212.0
35.3		50	281.0
85.3		100	327.8
135.3		150	358.4
185.3		200	381.8

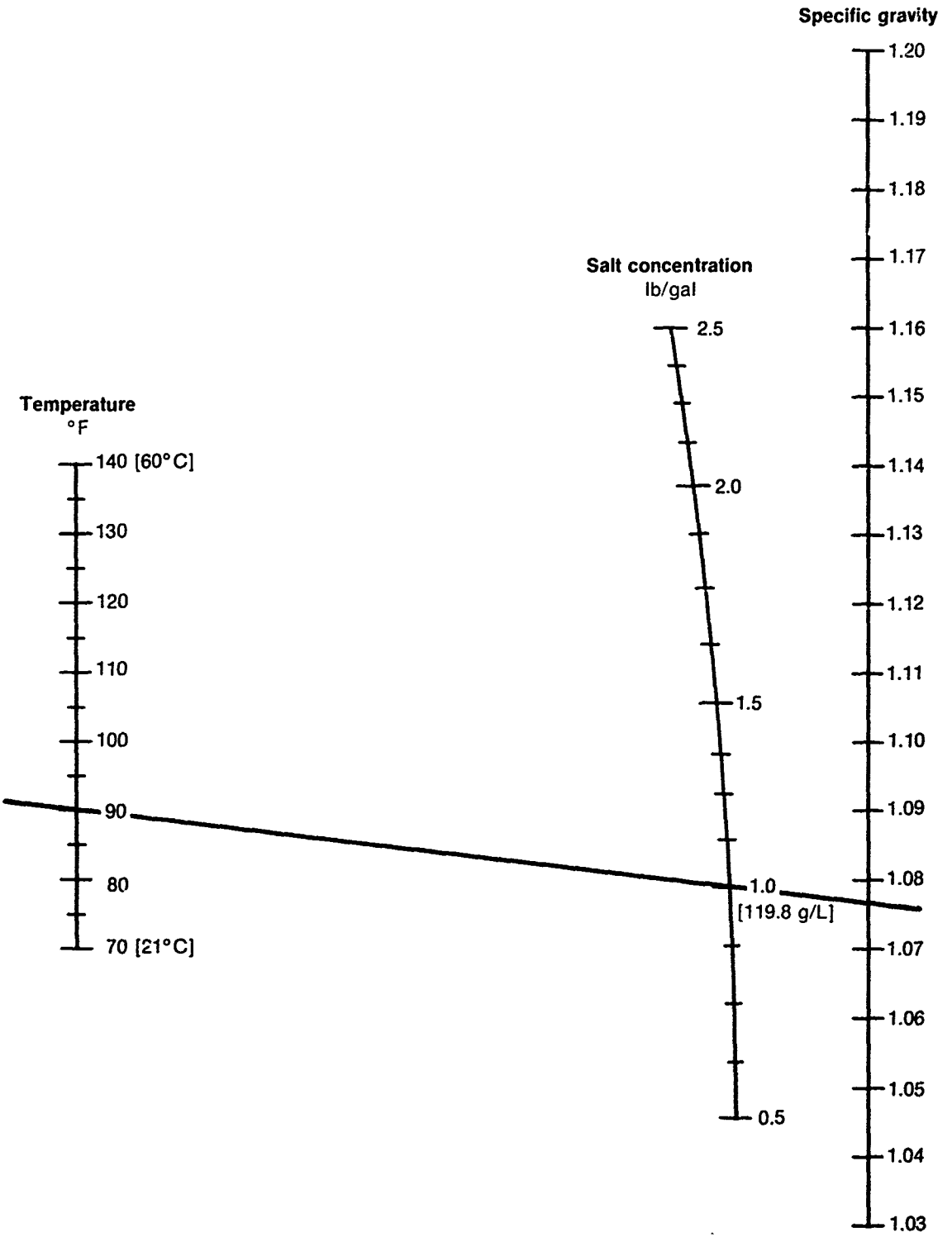


Figure 11.5–10 Nomogram to determine the specific gravity of sodium chloride solutions. Specific gravity measured by 60°F/60°F hydrometer. (Courtesy of Anocut Engineering Company)

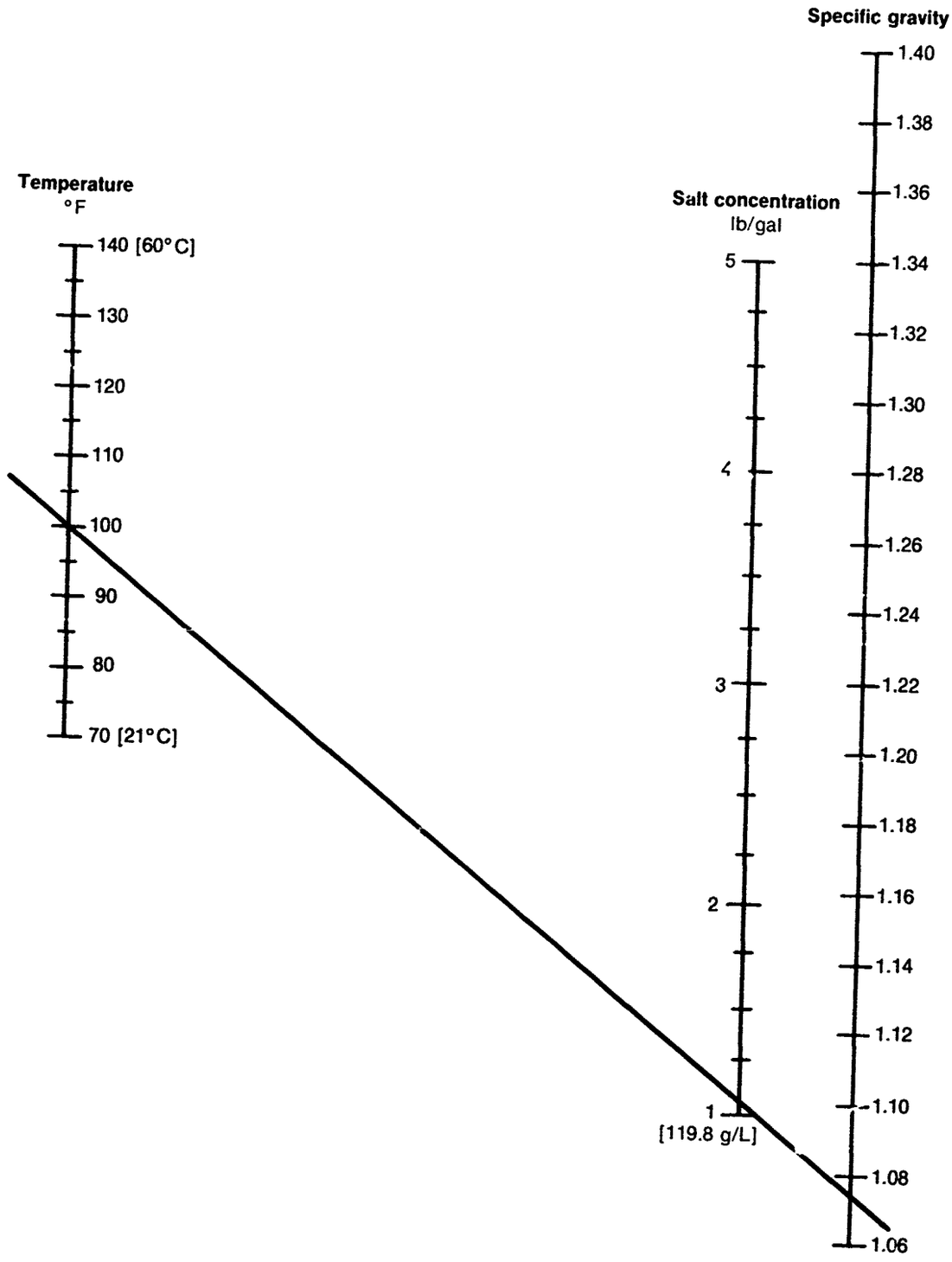


Figure 11.5–11 Nomogram to determine the specific gravity of sodium nitrate solutions. Specific gravity measured by 60°F/60°F hydrometer. (Courtesy of Anocut Engineering Company)

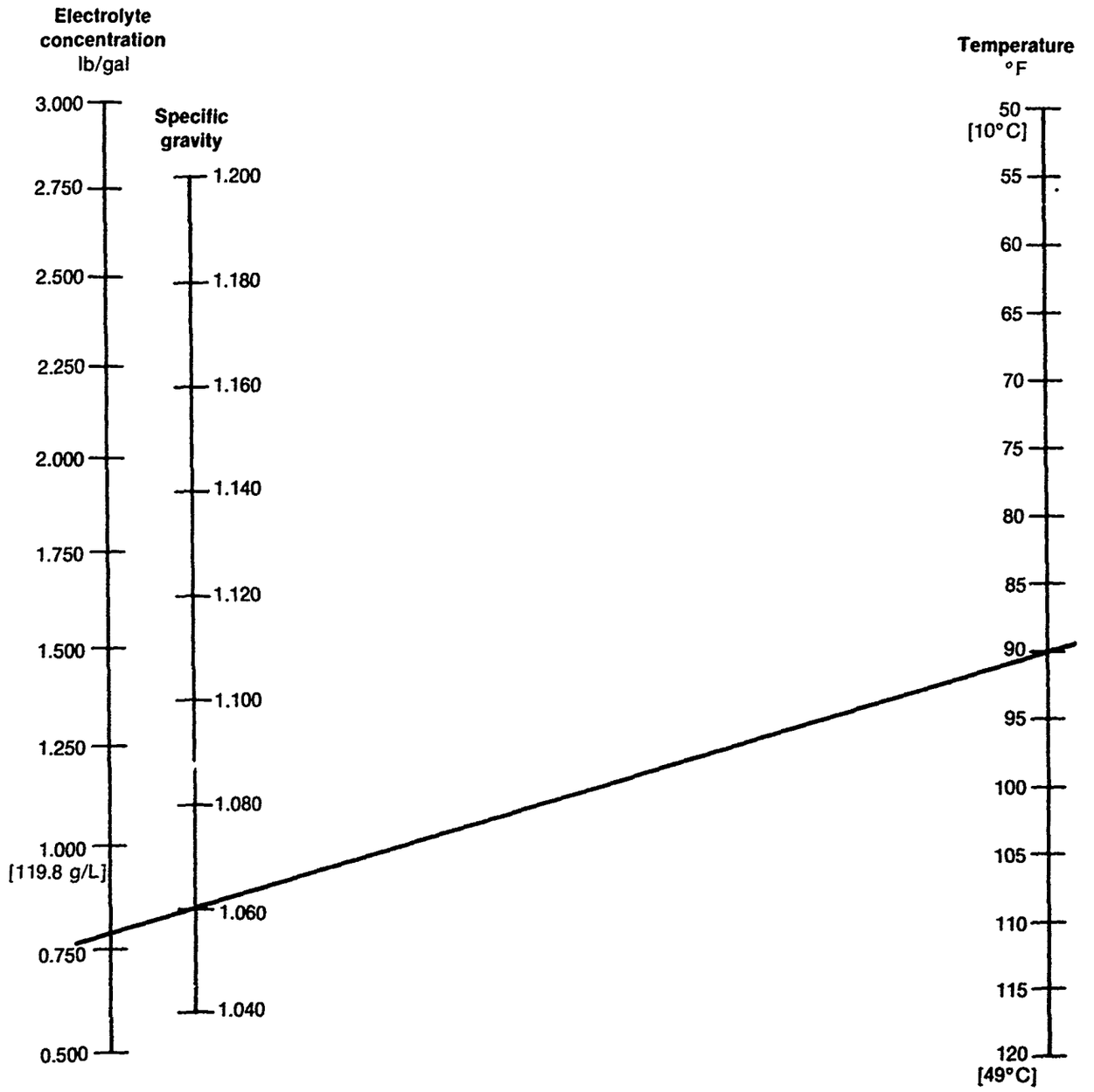


Figure 11.5–12 Nomogram to determine the specific gravity of 50 percent sodium chloride, 50 percent sodium nitrate solutions. (Courtesy of General Electric Company)

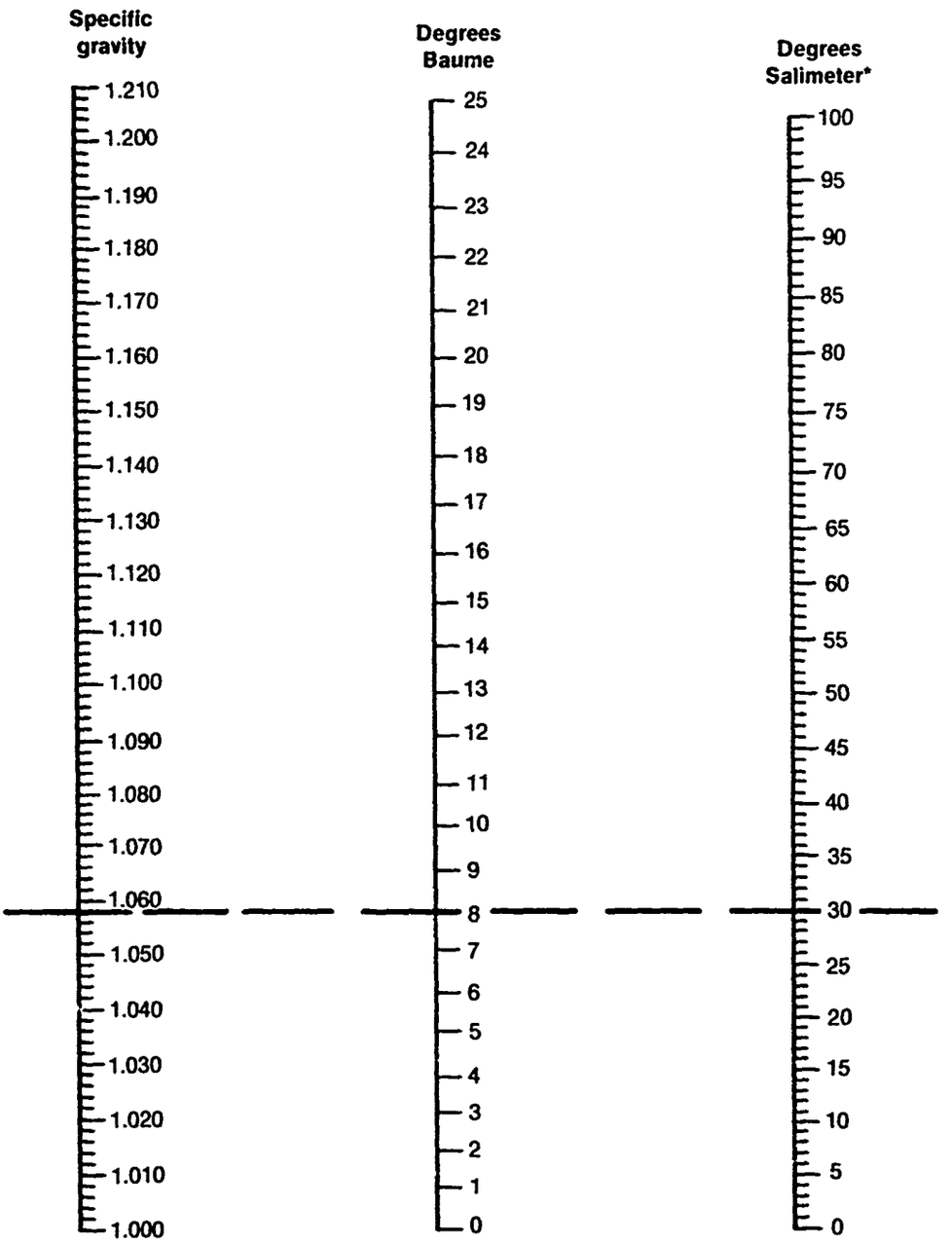
11.5 Electrochemical Machining—ECM

TABLE 11.5–8 Sodium Chloride (NaCl) Electrolyte Concentration Conversion Chart

HYDROMETER READING			CONCENTRATION/TEMPERATURE							
°Baume*	Specific Gravity	°Salimeter*	100°F lb/gal	38°C g/L	110°F lb/gal	43°C g/L	120°F lb/gal	49°C g/L	130°F lb/gal	54°C g/L
8	1.06	30	0.7	83.9	0.6	71.9	0.6	71.9	0.6	71.9
9	1.07	34	0.8	95.8	0.7	83.9	0.7	83.9	0.7	83.9
10	1.07	38	0.9	107.8	0.8	95.8	0.8	95.8	0.8	95.8
11	1.08	42	1.0	119.8	0.9	107.8	0.9	107.8	0.9	107.8
12	1.09	46	1.1	131.8	1.0	119.8	1.0	119.8	1.0	119.8
13	1.10	50	1 2	143.8	1.2	143.8	1.1	131.8	1.1	131.8
14	1.11	54	1.3	155.7	1.3	155.7	1.3	155.7	1.2	143.8
15	1.11	58	1.5	179.7	1.4	167.7	1.4	167.7	1.3	155.7
16	1.12	63	1.6	191.7	1.5	179.7	1.5	179.7	1 5	179.7
17	1.13	67	1.7	203.7	1.7	203.7	1.6	191.7	1.6	191.7
18	1.14	71	1.9	227.6	1.8	215.6	1.8	215.6	1.7	203.7
19	1.15	76	2.0	239.6	2.0	239.6	1.9	227.6	1.9	227.6
20	1.16	80	2.1	251.6	2.1	251.6	2.0	239.6	2.0	239.6
21	1.17	84	2.3	275.5	2.2	263.6	2.2	263.6	2.1	251.6
22	1.18	88	2.5	299.5	2.4	287.5	2.4	287.5	2.3	275.5
23	1.19	93	2.6	311.5	2.6	311.5	2.5	299.5	2.5	299.5
24	1.20	97	2.8	336.4	2.8	336.4	2.7	323.5	2.6	311.5
25	1.20	100	3.0	359.4	2.9	347.4	2.9	347.4	2.8	336.4

SOURCE: Cincinnati Milacron.

*Generally, a reading on the Baume scale is approximately the percentage of salt by weight. A reading on the Salimeter scale represents the percentage of saturation in a sodium chloride solution.



*Degrees Salimeter = 0.26395% salt by weight per degree salimeter.

Figure 11.5–13 Nomogram for salt concentration. Hydrometer scale comparison at 68°F. (Courtesy of International Salt Company)

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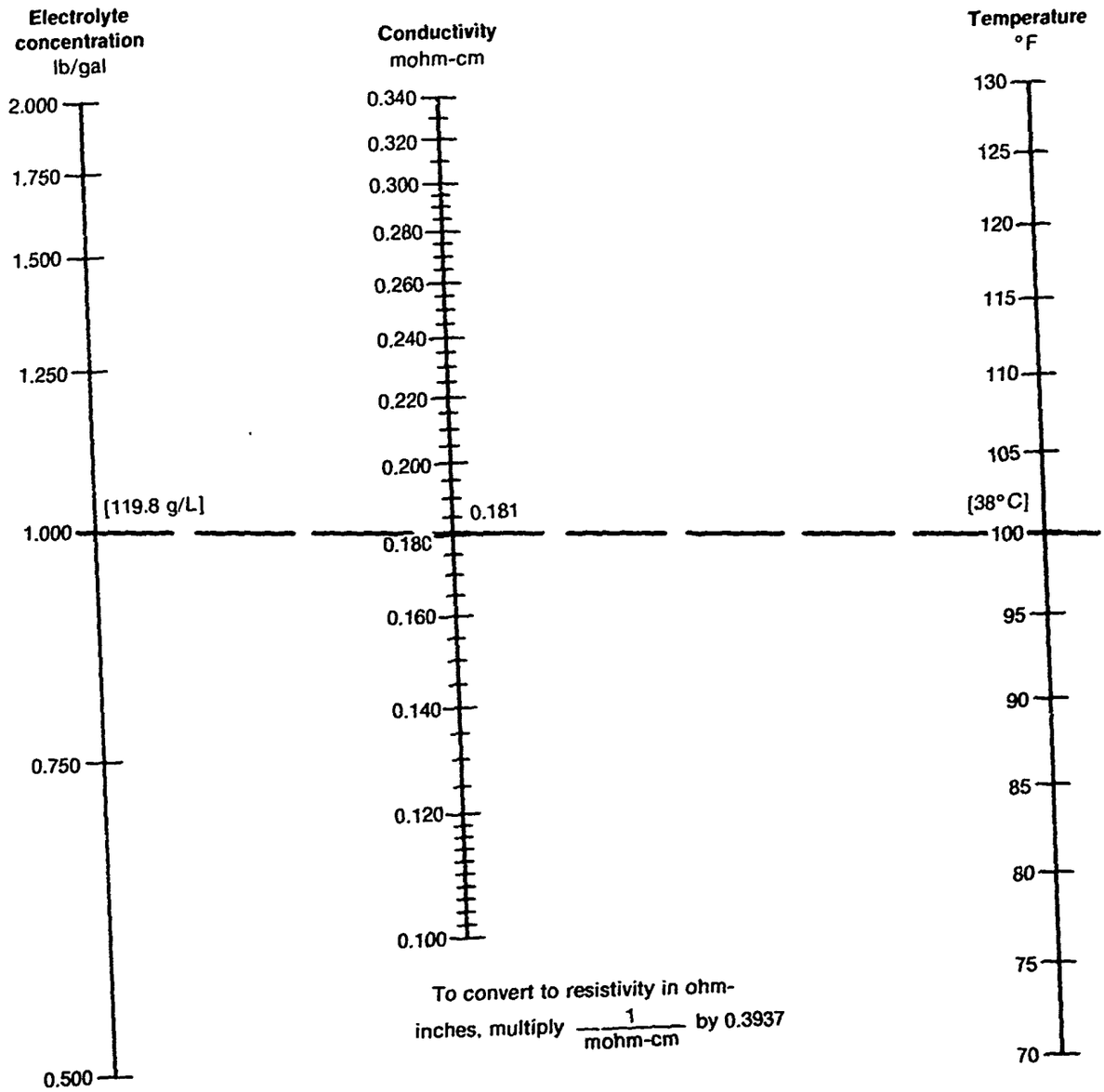


Figure 11.5–14 Nomogram to determine the conductivity of sodium chloride electrolytes. (J. A. Cross and A. U. Jollis, Electrochemical machining (ECM), Technical report AFML-TR-72-188, Vol. II, General Electric Company, 1972, p. 83)

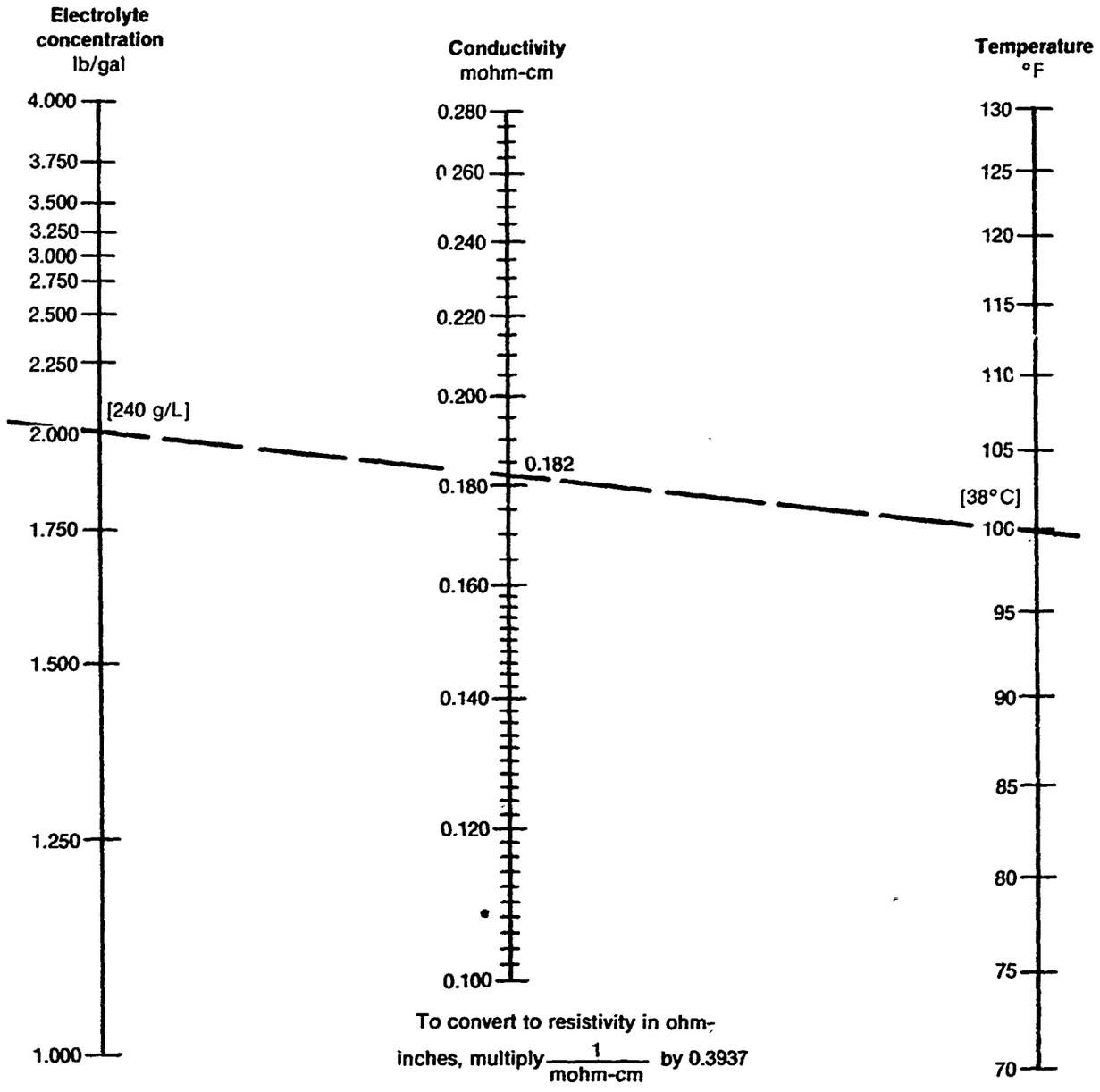


Figure 11.5–15 Nomogram to determine the conductivity of sodium nitrate electrolytes. (J. A. Cross and A. U. Jollis, p. 84)

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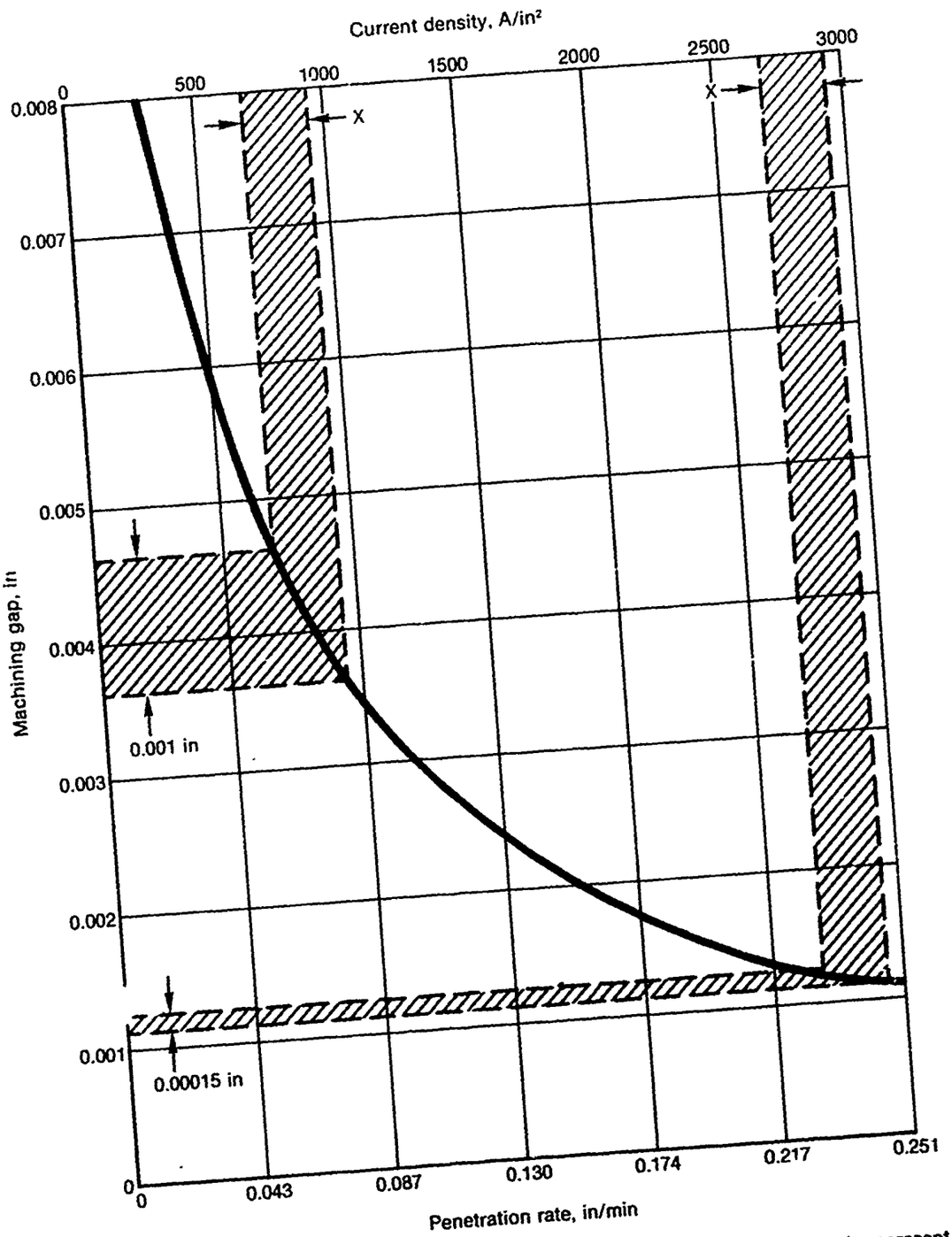


Figure 11.5–16 ECM of steel in a neutral electrolyte at 120°F and 15 volts. The "X" bands represent the variability expected in normal ECM. (Courtesy of Chemform Inc.)

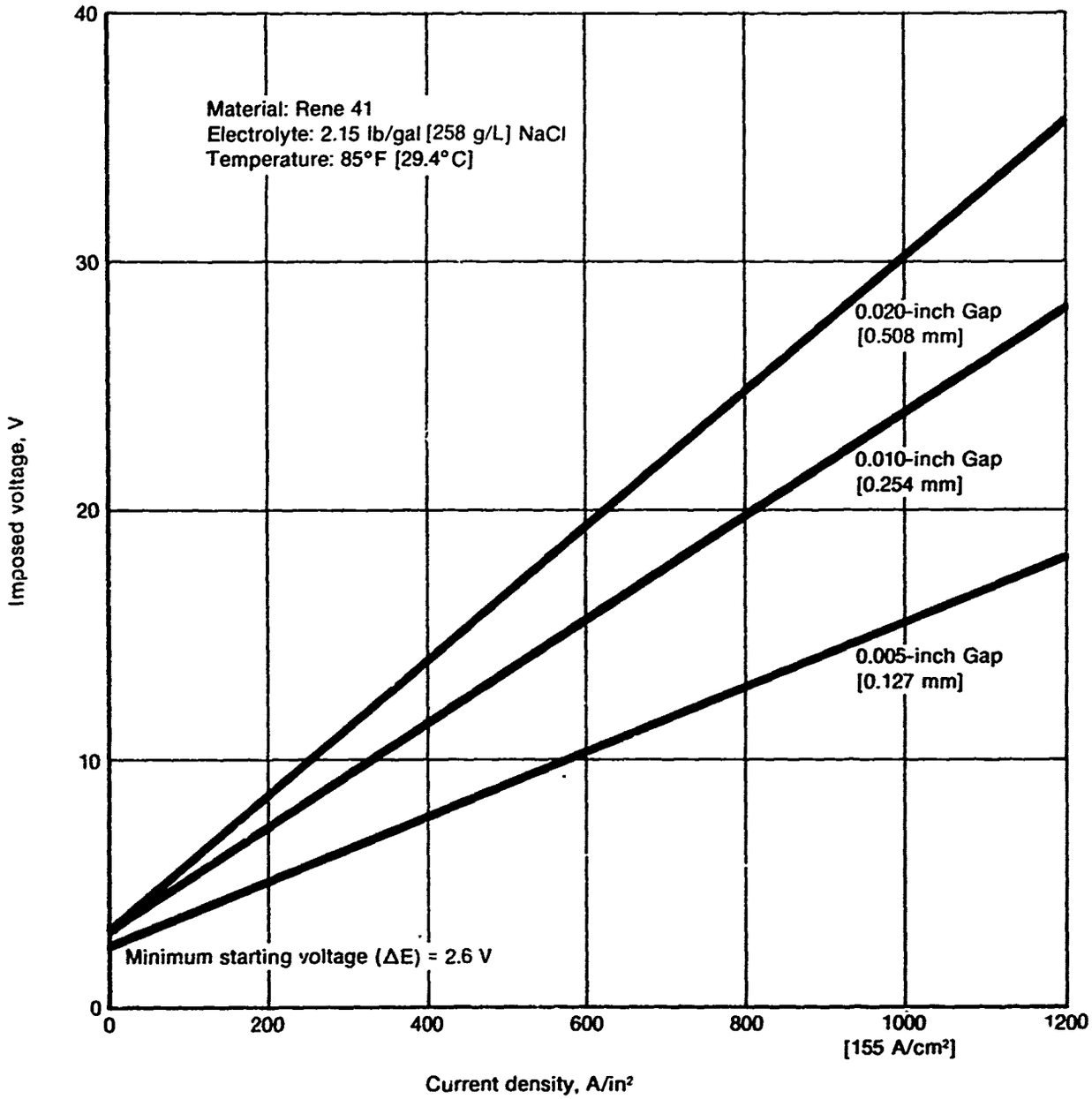
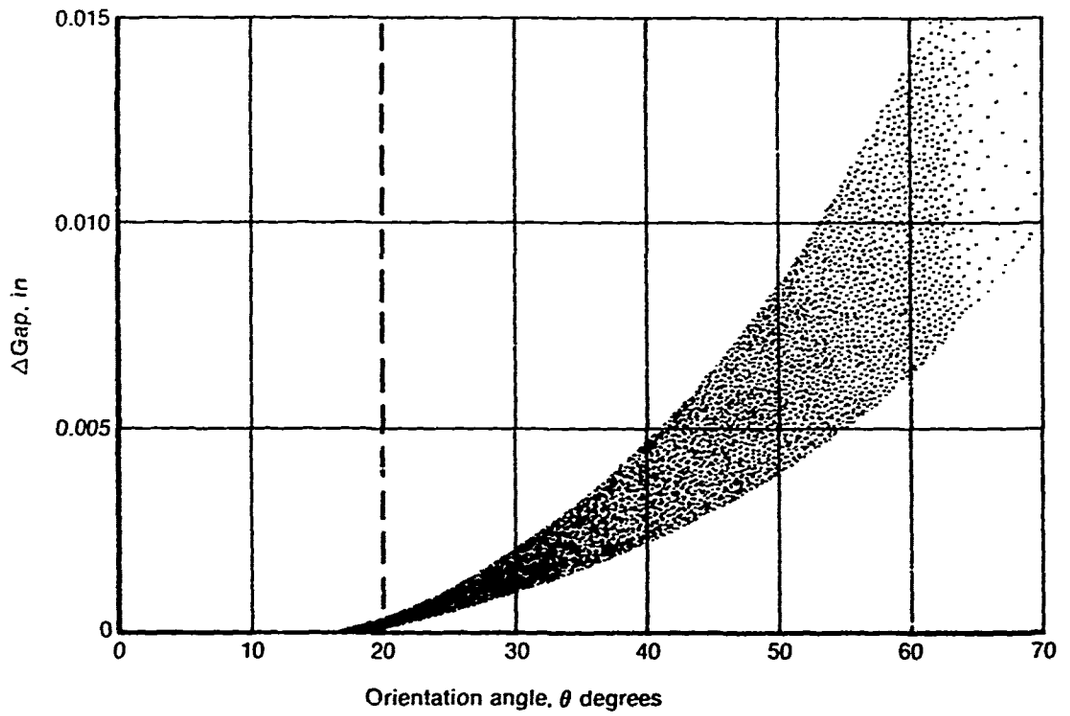


Figure 11.5–17 Specific gap selection data for specific alloy-electrolyte combination. (Note that figure 11.5–9 and 11.5–17 are the same data set.) (G. Bellows, ECM machinability data and ratings, Technical paper MR67-710, Society of Manufacturing Engineers, Dearborn, MI, 1967)

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- ANGLE θ — 0° to 20° (α = 70° to 90°)
  Use mirror or conjugate image of part and uniform gap. $S_c = S_e$.
- ANGLE θ — 20° to 40° (α = 50° to 70°)
  Correct tool shape from uniform gap to
  $S_c = S_e \sec\theta$ or $S_c = \frac{S_e}{\sin\alpha}$.
- ANGLE θ — greater than 40° (α less than 50°)
  Develop tool shape by trial cuts and correction.
- An Approximation:
  $\Delta Gap \cong S_e (\sec\theta - \cos\theta)$

Figure 11.5–18 Design of contour cutting electrodes in frontal ECM cutting under steady-state (equilibrium) process conditions.

TABLE 11.5-9 Typical Operating Conditions for ECM of Aerospace Alloys

WORKPIECE MATERIAL	ELECTROLYTE			MINIMUM STARTING VOLTAGE (ΔE)	METAL REMOVAL CONSTANT (k)*	
	Type	Concentration				
		oz/gal	g/L		in^3/A-min x 10^{-5}	cm^3/A-min x 10^{-3}
Inconel alloy 718, STA	NaCl	16	120	3.3	8.8	1.44
AF 95, STA (Rene 95)	$NaNO_3$†	36	270	4.3	10.3	1.69
Ti-6Al-6V-2Sn, Annealed	NaCl	16	120	3.2	10.2	1.67
Ti-6Al-4V, Annealed	NaCl	16	120	3 8	10.0	1.64
17-4 PH, STA	$NaNO_3$	36	270	3.6	8.6	1.41
300M, Tempered	NaCl	16	120	1.1	13 2	2.16
18%Ni Marage, STA	NaCl	16	120	1 0	13.2	2.16
MAR-M509, As cast	NaCl	16	120	1.2	9.6	1.57
Astroloy	$NaNO_3$	32	240	4.0	12.5	2.05

SOURCE J. A Cross and A U. Jollis, Electrochemical machining (ECM), Technical report AFML-TR-72-188, General Electric Company, 1972

*Used for estimating current required in formula

$$I = \frac{A_w v_f}{k}$$

I = current, amperes
A_w = area being machined, in^2 [cm^2]
v_f = feed rate, in/min [cm/min]
k = metal removal constant, in^3/A-min [cm^3/A-min]

See also figure 11.5-7 and table 11 5-3.

†Can also be cut satisfactorily with 16 oz/gal NaCl.

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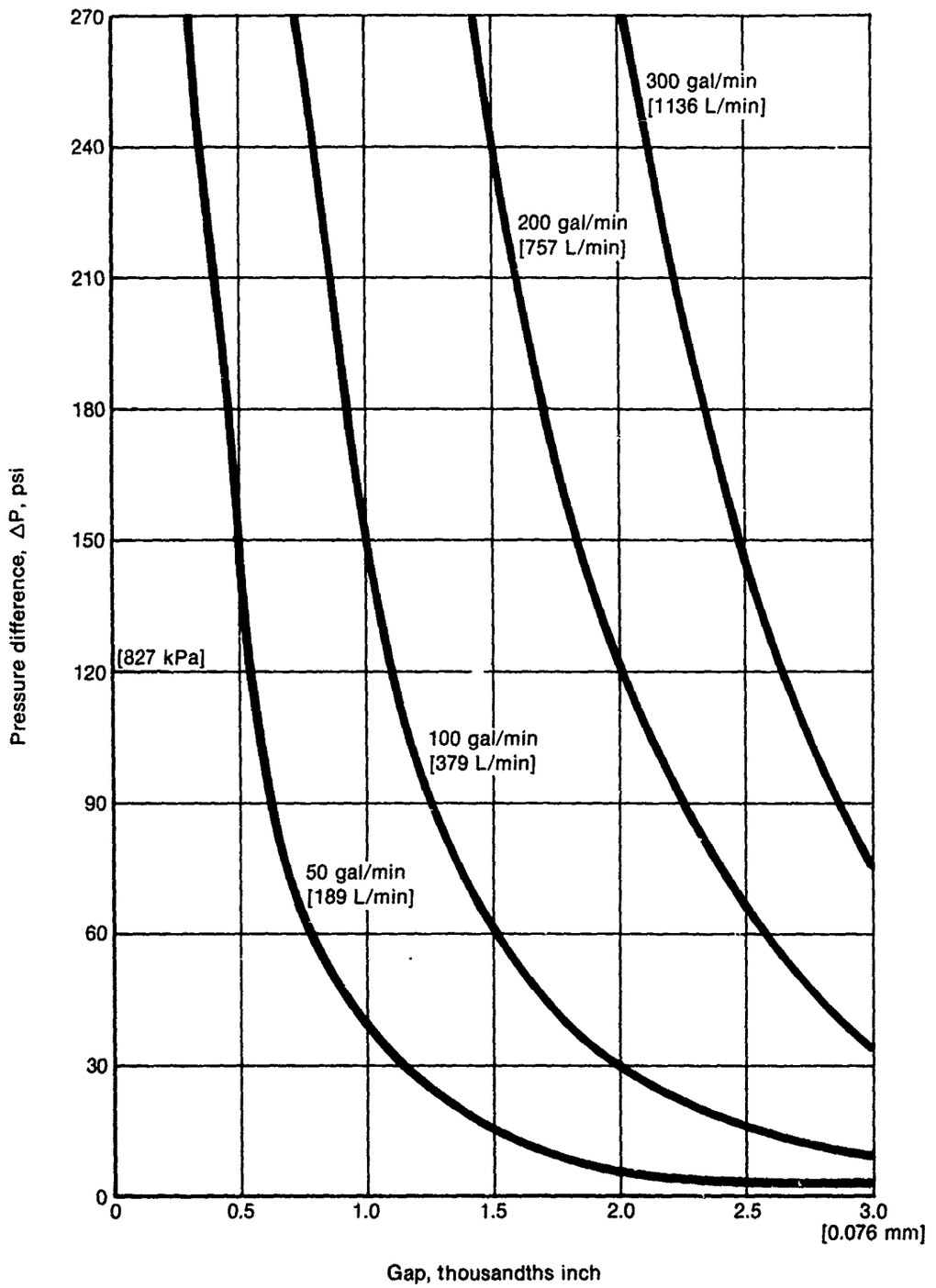


Figure 11.5–19 Theoretical pressure drop for an idealized cathode as a function of flow rate and gap size. (Courtesy of Anocut Inc.)

TABLE 11.5–10 Electrode and Tool Material Data for ECM

MATERIAL	ELECTRICAL RESISTIVITY microhm-cm at 20°C	COST	TENSILE STRENGTH (RT) ksi	TENSILE STRENGTH (RT) MPa	STIFFNESS (MODULUS ELASTICITY) psi x10⁶	STIFFNESS (MODULUS ELASTICITY) kPa x10⁴	THERMAL CONDUCTIVITY cal/cm²/cm/s/°C	MELTING POINT °F	MELTING POINT °C	SPARK RESISTANCE	REPAIRABILITY	COMMENTS
Copper (OF) as rolled	1.71	medium	58	400	17 6	121	0.934	1,980	1,082	poor	fair	Lowest resistivity.
Naval brass, (60Cu-39Zn)	6.63	low	75	517	15.0	103	0.287	1,640	893	poor	fair	Best general purpose electrode.
Bronze, commercial	3.8	medium	88	606	15.0	103	0.479	1,625	885	poor	fair	High silicon, aluminum or phosphor bronze can be used for additional strength
Austenitic stainless steel, 316 or other	73.0	high	85	586	29.0	200	0.039	2,525	1,385	good	good	Most easily repaired (by arc welding). Avoid for long electrodes.
Beryllium copper (heat treated)	7.8 (3.8 to 8.5)	high	110	758	16.0	110	0.139 to 0.277	1,780 to 1,990	970 to 1,088	poor	fair	High strength. Use for thin-wall electrodes when high electrolyte pressure required.
Copper tungsten	5.0 (varies with composition)	very high	low	low	—	—				very good	poor	Use when spark damage must be minimized.
Silver tungsten	4.0 (varies with composition)	very high	75	517	—	—				very good	poor	Use when spark damage must be minimized.
Tungsten, ductile	13.1	very high	130	896	53	365	0.264	6,126	3,386	excellent	poor	Difficult to fabricate.
Titanium alloys	170	high	61	420	16.0	110	0.098	3,272	1,800	fair	fair	Good corrosion resistance.
SAE 1045 carbon steel	16.2	low	95	655	29.5	203	0.141	2,700	1,482	poor	good	Not recommended for electrodes, corrodes easily.

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TABLE 11.5–11 Insulating Materials for ECM

MATERIAL	TYPICAL SOURCE	METHOD OF APPLICATION
#260 Epoxy powder	3M Company	Spray or fluid-bed dip
E-201 Epoxy powder	Armstrong Resins Inc.	Spray or fluid-bed dip
Microsol E-1003	Michigan Chrome & Chemical	Liquid dip
Anocoat 6004 epoxy putty	Anocut Inc.	Knife
Anocoat 6005	Anocut Inc	Brush
Anocoat 6006	Anocut Inc.	Spray or fluid-bed dip
Plexiglass	Various	Fabricate (for short life applications)
Epoxy-glass laminates	Various	Fabricate
Textolite 11558 (NEMA G10, sometimes called green glass)	General Electric Co.	Fabricate

TABLE 11.5–12 Organic Coatings to Protect Metals from Corrosion by ECM Electrolytes

COATING	CHEMICAL RESISTANCE			RESISTANCE TO ABRASION	REMARKS
	Dilute Hydrochloric and Sulphuric Acids	Brine Solution	Dilute Alkalis		
Polyvinyl chloride (PVC)	S	S	S	Good	
Polythene (high density)	S	S	S	Good	Preferred to the low density material for electrical applications
Polythene (low density)	S	S	S	Fair	
Nylon	Limited	S	Limited	Very good	Very low water absorption. Electrical insulation excellent
PTFE	Good, but difficult to obtain coatings free of pores			Poor	
Chlorinated polyether (Penton)	S	S	S	Very good	
Solvent-based epoxy resin	Generally S, depending on formulation	S	As for acids	Good	Oven-drying preferred to air-drying
Solventless epoxy resin	S	S	S	Good	Better performance than solvent-based compositions
Polyurethane	S	S	S	Said to be similar to vitreous enamel	
Chlorinated rubber	S	S	S	Good	
Neoprene	Limited	S	S	Very good	

SOURCE: A. E. De Barr and D. A. Oliver, *Electrochemical machining* (New York: American Elsevier, 1967), p. 181.
NOTE: S = Satisfactory

TABLE 11.5–13 Volume Ratio and Specific Gravity for ECM Sludge
(Ratio of volume of sludge to volume of metal removed for sodium chloride (NaCl) electrolytes)

WORKPIECE MATERIAL	VOLUME RATIO	SPECIFIC GRAVITY
Nickel base alloy	250:1	1.3
Titanium base alloy	500:1	1.1
Iron base alloy	150:1	1.3

SOURCE: J. A. Cross and A U. Jollis, Electrochemical machining (ECM), Technical report AFML-TR-72-188, General Electric Company, 1972.

11.5 Electrochemical Machining—ECM

SPECIFIC APPLICATIONS DATA

TABLE 11.5–14 Specific Applications Data for Electrochemical Machining

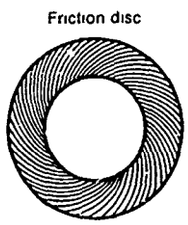
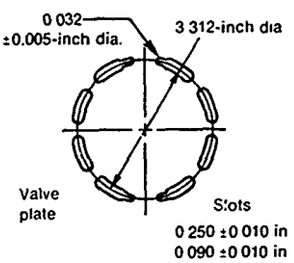
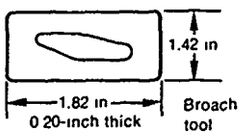
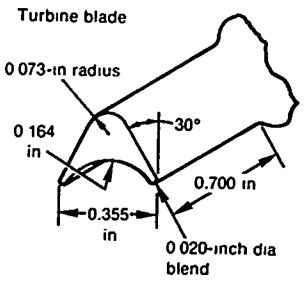
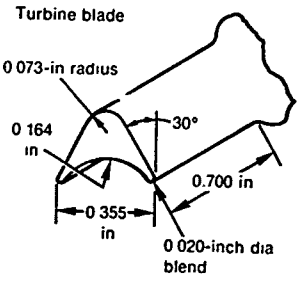
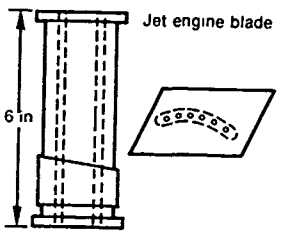
Work material:	SAE 1020 Steel, 60–75 R_B	52100 Steel, 65 R_c	T15 Tool Steel
Workpiece configuration:			
Electrolyte type:	NaCl	NaCl	NaCl
concentration, lb/gal:	1.25	1.7	1.0
inlet pressure, psi:	60 to 100	100 to 150	200
outlet pressure, psi:	0	0	0
flow rate, gal/min:	10	18 to 20	
temperature, °F:	85 to 90	90	100
Voltage, dc volts:	20	13	13
Current, A start:	650	1,500	200
end:	600	2,200	250
Feed rate, in/min:	zero (static tools)	0.150	0.094
Depth of cut, in:	0.015	0.330	0.2
Tolerance, in:	±0.005	±0.007	±0.005
Surface roughness, μin R_a:	burr free	25 to 50	30
Electrode material, filtration, benefits and remarks:	Brass electrode. 10 μm (micron) filters. 5-second dwell time. 72 grooves spaced at 5° intervals for 360° both sides. Groove width 0.040 inch; thickness 0.0693 inch ±0.0035 inch. One side machined at a time.	Brass electrode. 50 μm (micron) filters. All 8 kidney slots machined simultaneously.	Two pieces cut simultaneously. Piercing cut.

TABLE 11.5–14—Continued

Work material:	**A286, 25 R_c**	**Waspaloy**	**Udimet 700, forged**
Workpiece configuration:			
Electrolyte type:	$NaNO_3$	NaCl	H_2SO_4
concentration, lb/gal:	2.2	1.7	10% solution
inlet pressure, psi:	130 to 200	130 to 200	15
outlet pressure, psi:	0	0	0
flow rate, gal/min:	2	2.5	0.6
temperature, °F:	110	90	95
Voltage, dc volts:	11	12	9 with periodic reversal
Current, A start:	100	100	3
end:	150	150	10
Feed rate, in/min:	0.300	0.325	0.050
Depth of cut, in:	7.0	7.0	3.0
Tolerance, in:	±0.004	±0.004	±0.002
Surface roughness, μin R_a:	15 to 25	10 to 20	63 to 120
Electrode material, filtration, benefits and remarks:	Copper-tungsten electrode. 50 μm (micron) filters. Constant section turbine blade.	Copper-tungsten electrodes. 50 μm (micron) filters. Constant section turbine blade.	Insulated titanium tubes as electrodes. 10 μm (micron) filters. 6 holes of slightly different sizes machined simultaneously. See also STEM process.

11.5 Electrochemical Machining—ECM

TABLE 11.5–14—Continued

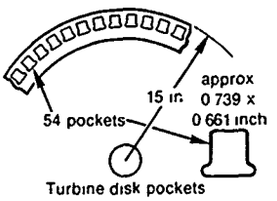
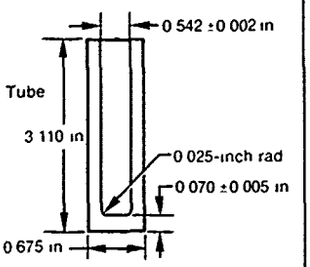
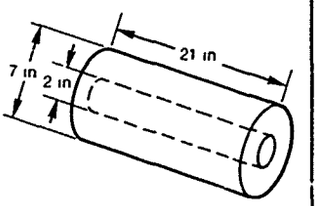
Work material:	**Inconel Alloy 718, STA**		**Tungsten**	**Uranium, 53–57 R_A**
Workpiece configuration:				
Electrolyte type:	NaCl	NaCl	NaOH	NaCl
concentration, lb/gal:	1.0 ±0.1	1.0	1.5	1.0
inlet pressure, psi:	225 to 275	100, start; 160, end	50	150
outlet pressure, psi:	25 to 75	60, start; 40, end	0	0
flow rate, gal/min:	15 (est.)	290, start; 235, end	3	
temperature, °F:	105 ±5	100	80	110
Voltage, dc volts:	18	11	10	12.5
Current, A start:	130 (est.)	2,800 to 3,500	450	400 (est.)
end:	630	16,000 to 18,000	450	800
Feed rate, in/min:	0.060	0.032	none	0.10
Depth of cut, in:	0.2	0.3	3.04	11
Tolerance, in:	±0.003	±0.003	±0.002	±0.010
Surface roughness, μin R_a:	30 to 40, front; 75 to 150, side	70 to 90	10	
Electrode material, filtration, benefits and remarks:	Copper electrodes. 75 μm (micron) filter. Single pocket per stroke.	Brass electrodes (an assembly of 54 separate replaceable units). All 54 pockets per stroke. Nine-minute machining cycle.	Copper electrodes. 50 μm (micron) filter. Bore enlargement from 0.535 to 0.542 inch. Similar to ECP.	Copper tubing electrode. Trepanned ¿-inch hole through 21-inch ingot. (Ingot turned end for end after penetration of the tool had reached one half the length of ingot.)

TABLE 11.5–14—Continued

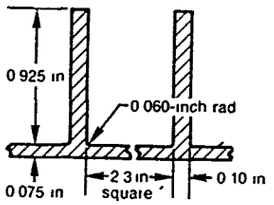
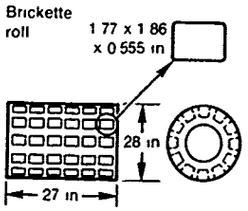
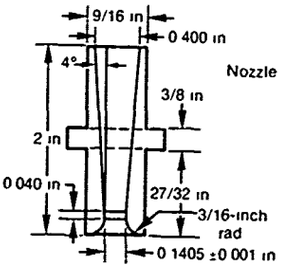
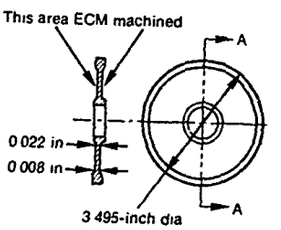
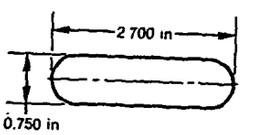
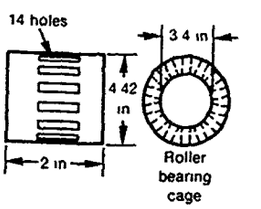
Work material:	Ti-6Al-4V	HC250 Alloy Steel, 54 R_c	316 Stainless Steel
Workpiece configuration.			
Electrolyte type:	NaCl	NaCl	NaCl
concentration, lb/gal.	1.0	1.0	1.0
inlet pressure, psi:	190 ± 10	210	80
outlet pressure, psi:	10 (est.) reverse flow	150	0
flow rate, gal/min:	50 (est.)		2
temperature, °F:	115 to 125	100	80
Voltage, dc volts:	13	15	17
Current, A start:	2,000 (est.)	3,000	20
end:	2,400	9,000	310
Feed rate, in/min:	0.050	0.060	0.230
Depth of cut, in:	0.925	0.555	1.74
Tolerance, in:	±0.002	±0.015	4° taper
Surface roughness, μin R_a:	22 to 28, bottom; 120 to 240, side	70	5 to 10
Electrode material, filtration, benefits and remarks:	Copper-tungsten electrodes (side insulation). 0.008-inch front gap. 0.030-inch side gap (overcut). 0.060-inch corner radii.	7 pockets cut simultaneously. 630 pockets in 45 rows of 4 each. One indexing vertically per row.	Copper electrode. 50 μm (micron) filters.

TABLE 11.5-14—Continued

Work material:	18% Ni Maraging Steel	Inconel Alloy X750	4340 Steel	
Workpiece configuration:				
Electrolyte type:	NaCl	$NaCl + NaNO_3$	NaCl	NaCl
concentration, lb/gal:	1.25	1.33 + 0.67	1.0	1.0
inlet pressure, psi:	60 to 100	80 (est.)	200	200
outlet pressure, psi:	0	20 (est.)	125	50
flow rate, gal/min:	17	10 (est.)		
temperature, °F:	110	100 (est.)	100	100
Voltage, dc volts:	6.5	17	15	10.5
Current, A start:	1,000	400	5,000	1,000
end:	2,600	1400	6,000	1,200
Feed rate, in/min:	0.076	0.080	0.195	0.400
Depth of cut, in:	0.090	1.250	0.50	0.50
Tolerance, in:	±0.0003 on thickness	±0.003 (est.)	Trepanning roughing cut	Finish cut ±0.002
Surface roughness, μin R_a:	4 to 10	35 to 50		30 max.
Electrode material, filtration, benefits and remarks:	Copper electrode. 100 μm (micron) filter. Workpiece rotated at 125 rpm (or ECT). One side machined at a time. Waffle grid of pockets.	Copper-tungsten electrode. Through-hole slot.	Five parts cut simultaneously. Trepanning roughing cut followed by finishing cut. 30 minute floor-to-floor time per part.	

PROCESS SUMMARY

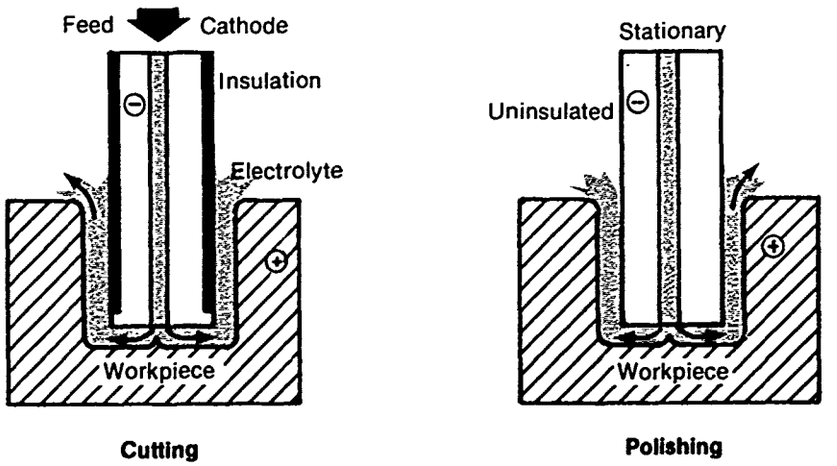


Figure 11.6-1 ECP schematic.

Principles

Electrochemical polishing (ECP) is a special form of electrochemical machining (ECM) arranged for cutting or polishing a workpiece (see figure 11.6-1). Polishing parameters are similar in range to those for cutting, but without the feed motion. ECP generally uses a larger gap and a lower current density than does ECM. This requires modestly higher voltages. (In contrast, electropolishing (ELP) uses still lower current densities, lower electrolyte flow and more remote electrodes.)

Sometimes, after ECM of a cavity, the ECM electrode is allowed to dwell at the end of the cut to accomplish a polishing action. Dwelling must be performed under carefully selected conditions and timing to prevent a bulge in the cut. Occasionally, the ECM electrode is retracted slightly (to double or triple the cutting gap) to promote better electrochemical polishing. An uninsulated electrode may also be inserted in place of the cutting electrode to polish the side walls of deep pockets.

Practical Applications

The special efforts and electrodes required for ECP can be justified for high production or unusual applications on difficult-to-machine materials. Very fine finishes can be achieved with only a few seconds exposure. With proper insulation, only selected portions of the workpiece will receive the extra polishing. The rougher side walls on deep ECM cavities can be smoothed by the use of an uninsulated electrode.

Operating Parameters

ECP operates in the same manner as does regular ECM; however, the values of the operating parameters are modified slightly. For ECP, the working gap is larger, typically 0.020 inch [0.50 mm]; the current density is much lower, less than or equal to 25 percent of cutting level; and the voltage is higher, up to 50 percent. The electrolyte flow rate is maintained at its usual high level.

Material Removal Rates, Tolerances and Surface Technology

ECP removes insignificant amounts of material—only ten-thousandths inch. The accuracy of the timing of the "on" cycle controls the tolerances and the surface roughness. A surface roughness of 12 microinches R_a [0.3 μm] can be attained easily in stainless steels or nickel alloys.

Equipment and Tools

ECP requires modification of the electrodes and operating conditions of regular ECM equipment.

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Electrochemical Sharpening—ECS 11.7

PROCESS SUMMARY

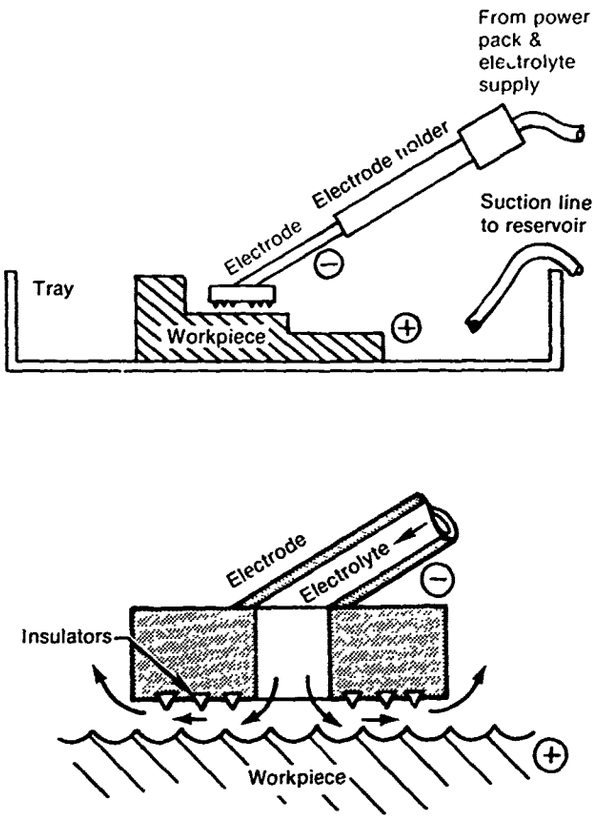


Figure 11.7–1 ECS schematic.

Principles

Electrochemical sharpening (ECS) is a special form of electrochemical machining arranged to accomplish sharpening or polishing by hand (see figure 11.7–1). A portable power pack and electrolyte reservoir supply a finger-held electrode with a small current and flow. The fixed gap incorporated on the several styles of shaped electrodes controls the flow rate. A suction tube picks up the used electrolyte for recirculation after filtration.

Practical Applications

Rapid, localized finishing to low roughness levels can be achieved on any conductive material. Spot removal of unwanted recast layers or heat-affected areas is practical as part of a finishing bench operation.

Operating Parameters

For ECS, only 10 amperes or less are required for the small electrodes and fractional gallon-per-minute flow rates. The voltage range is similar to that for ECM, 8 to 18 volts.

Material Removal Rates, Tolerances and Surface Technology

ECS smooths without significant material removal. Roughness levels of 30 microinches R_a [0.8 μm] from an initial 63 microinches R_a [1.6 μm] are possible with a few seconds application.

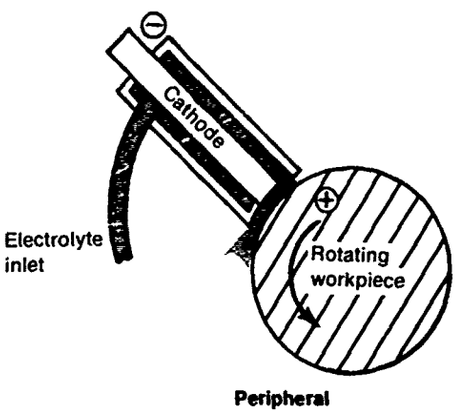
Equipment and Tools

ECS equipment has been packaged into a portable set; however, any small power pack, tray and pump arrangement suitable for use with the salt electrolytes can be adapted for use for this process.

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Electrochemical Turning—ECT 11.8

PROCESS SUMMARY



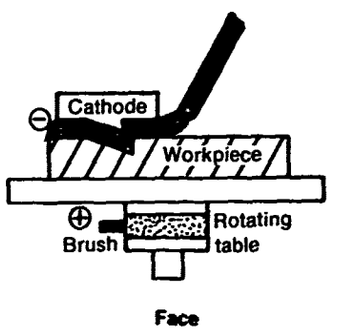


Figure 11.8–1 ECT schematic.

Principles

Electrochemical turning (ECT) is a special form of electrochemical machining designed to accommodate rotating workpieces (see figure 11.8–1). The rotation provides additional accuracy but complicates the equipment with the method of introducing the high currents to the rotating part. Electrolyte control may also be complicated because rotating seals are needed to properly direct the flow. Otherwise, the parameters and considerations of electrochemical machining apply equally to the turning mode.

Practical Applications

Both peripheral and face cuts are practical on electrically conductive materials. Roughing of large disk forgings is practical with electrochemical turning. Some shops have plunged a full-face electrode into the face of the rotating disk. Turning of inside diameters has also been accomplished. ECT can be used to finish parts such as bearing races to close tolerances with surface roughness values better than 5 microinches R_a [0.1 μm].

Operating Parameters

The operating parameters and typical values are similar to those for electrochemical machining, section 11.5.

Material Removal Rates, Tolerances and Surface Technology

ECT attains the same values as those for electrochemical machining.

Equipment and Tools

ECT equipment is available by special order for face, internal or peripheral turning. Capacities range up to 20,000 amperes.

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Electro-stream™—ES 11.9

PROCESS SUMMARY

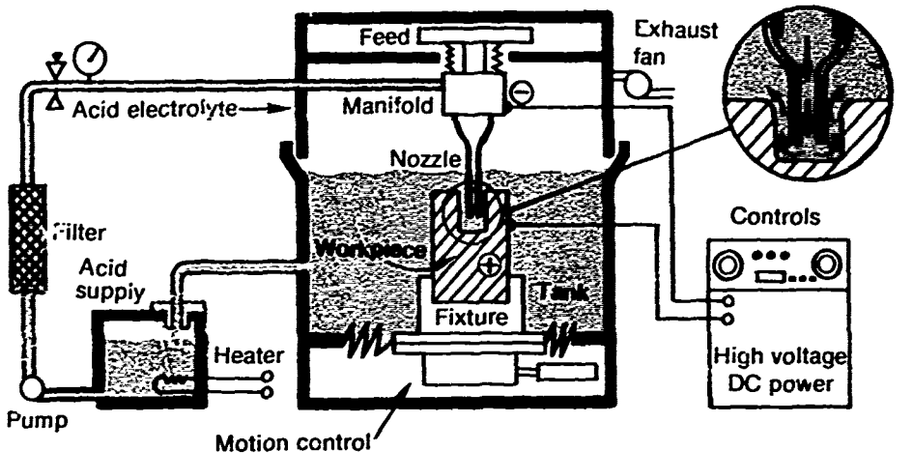


Figure 11.9–1 ES schematic.

Principles

Electro-stream™ (ES) is a special version of electrochemical machining adapted for drilling very small holes using high voltages and acid electrolytes (see figure 11.9–1). The voltages are more than 10 times those employed in ECM or STEM™, so special provisions for containment and protection are required. The feed must be controlled to match exactly the rate of dissolution of the workpiece material. Temperature, pressure, concentration and flow control are needed for the acid electrolyte, which is chosen to be chemically compatible with the workpiece metallurgical state. For corrosion protection, both the feed and the motion mechanisms are in pressurized chambers, separated from the acid electrolyte. The actual drilling takes place in a plastic chamber, suitably vented, with controls for automatic rapid advance of the tool, close programming of feed, dwell at hole breakthrough, if desired, and rapid retraction prior to indexing to the next location. The tool is a drawn-glass nozzle, one or two thousandths inch smaller than the desired hole size. An electrode inside the nozzle or the manifold ensures electrical contact with the acid. Multiple hole drilling predominates.

Practical Applications

Holes ranging from 0.008- to 0.040-inch [0.2 to 1 mm] diameter with depth-to-diameter ratios up to 50:1 can be made in any conductive material. Table 11.9–1 lists materials that have been drilled with ES. Holes can be drilled at angles as shallow as 10 degrees. A principal application is the drilling of cooling holes in gas turbine components which are usually fabricated from nickel and cobalt alloys. Insertion of a nozzle with a formed tip permits right-angle drilling deep inside prior holes or cavities. Over 70 holes per machine stroke have been accomplished on multiple parts; automatic indexing permits the drilling of several hundred holes per part. One example is the drilling of 96 holes simultaneously in the leading edge of a superalloy gas turbine vane. Over 100,000 such parts have been drilled with a reject rate of 1-1/2 percent and an average drilling time of one minute per part. Up to 0.75-inch [19 mm] deep holes can be drilled.

TABLE 11.9–1 Some Materials that Have Been Drilled Using ES

With HCl:	
	Aluminum
	IN-100
	Ti-6Al-4V
	SEL 15
With H_2SO_4:	
	1010 Carbon steel
	304 Stainless steel
	316 Stainless steel
	321 Stainless steel
	8630 Alloy steel
	Udimet 700
	Rene 41
	Rene 77
	Rene 80
	Rene 100
	Rene 120
	Rene 125
	IN-102
	Inconel alloy 625
	Inconel alloy 718
	IN-738
	Inconel alloy X-750
	Incoloy alloy 825
	Hastelloy alloy C
	Hastelloy alloy X
	HS-31 (X-40)
	Haynes alloy 25 (L605)
	Haynes alloy 188

11.9 Electro-stream™—ES

Operating Parameters

TABLE 11.9-2 Typical Values for ES Operating Parameters

Power supply	
type:	Direct current
voltage:	150 to 850 V
current:	20 to 200 milliamperes/hole (not independently adjustable)
Electrolyte	
type (s):	H_2SO_4, HCl, or proprietary mixtures
concentration:	5 to 15%
temperature:	80° to 120°F [27° to 49°C]
pressure:	20 to 100 psi [138 to 689 kPa]
contamination:	6 g/L max
Feed rate:	0.030 to 0.180 in/min [0.76 to 4.6 mm/min]
Hole diameter:	0 008 to 0.040 inch [0.2 to 1 mm]
Hole depth:	Up to 0.75 inch [19 mm]
Depth-to-diameter ratio:	Up to 50:1
Holes per stroke:	Up to 100
Drilling angle:	10° to 170°
Diameter tolerance:	±0.001 inch [0.025 mm] or ±5% of hole diameter
Surface roughness:	16 to 63 μin R_a [0.4 to 1.6 μm]

Material Removal Rates and Tolerances

Penetration rates of 1 to 2 thousandths inch per second [0.025 to 0.050 mm/s] are typical for the superalloys. The electrolytic dissolution follows Faraday's laws (see section 11.5), and current density is limited by the boiling of the electrolyte in the nozzle from the resistive heating. Diameter tolerance is typically ±0.001 inch [±0.025 mm] or plus or minus 5 percent for sizes above 0.020 inch [0.5 mm]. Straightness is 0.0005 inch per inch [0.0005 mm/mm].

Surface Technology

Surface roughness in the holes ranges from 16 to 63 microinches R_a [0.4 to 1.6 μm]. There are no metallurgical changes when the electrolyte and operating parameters are compatible with the metallurgical state of the workpiece, nor are there process-induced residual stresses in the surfaces. Thermal damage is nonexistent. Surface imperfections frequently are a reflection of material inhomogeneity rather than process variability.

Equipment and Tools

ES equipment is available from the General Electric Company, Cincinnati, Ohio 45216. Equipment can be provided with all the ancillary devices needed to operate the system. Fixturing requires the careful selection of materials suitable for the process environment. The nozzles are drawn from special glasses and are designed for penetration either in the feed mode or in the stationary, "dwell" mode.

Machining Characteristics

The highly corrosive environment can shorten the life of the equipment unless exceptionally good maintenance is rendered. Adjacent equipment must also be protected. Disposal of the metal-ion-contaminated electrolyte must be carried out in an environmentally satisfactory manner.

Shaped Tube Electrolytic Machining—STEM™ 11.10

PROCESS SUMMARY

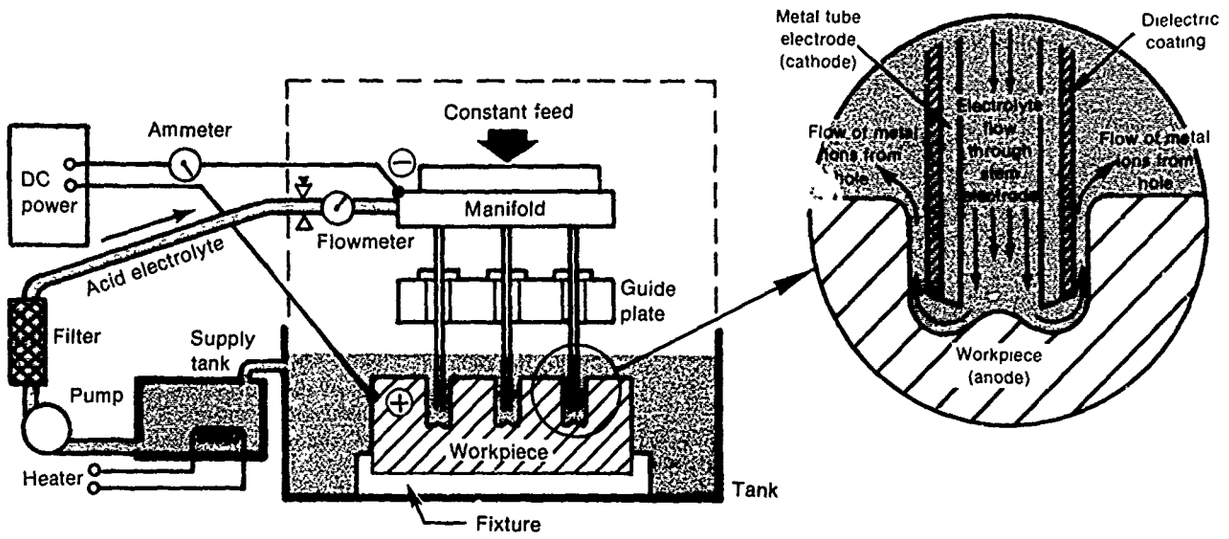


Figure 11.10-1 STEM™ schematic.

Principles

Shaped tube electrolytic machining (STEM™) is a specialized ECM technique for "drilling" small, deep holes utilizing acid electrolytes (see figure 11.10-1). Acid is used so that the dissolved metal will go into the solution rather than form a sludge, as is the case with the salt-type electrolytes of ECM. The electrode is a carefully straightened, acid-resistant, metal tube. The tube is coated with a film of enamel-type insulation. The acid is pressure fed through the tube and returns via a narrow gap between the tube insulation and the hole wall. The feed, constant within plus or minus one percent, advances the electrode into the workpiece at a rate exactly equal to the rate at which the workpiece material is dissolved. Multiple electrodes, even of varying diameters or shapes, may be used simultaneously. A guide plate is used to direct the electrodes. A solution of sulfuric acid is frequently used as the electrolyte when machining the nickel alloys. The electrolyte is heated and filtered, and flow monitors control the pressure. Tooling is frequently made of plastics, ceramics or titanium alloys to withstand the electrified, hot acid. The electrode can be shaped to drill odd cross sections, and, within the yield limits of the tooling material, divergent holes may be drilled simultaneously. The voltage used is modest and is reversed periodically for a fraction of a second to remove any film buildup on the electrode, but not long enough to remove substantial material that would change the electrode shape.

Practical Applications

STEM™ is used to drill round or shaped holes in difficult-to-machine conductive materials. Table 11.10-1 lists materials that have been drilled using STEM™. Holes as deep as 24 inches [610 mm] can be produced with length-to-diameter ratios up to 300:1 and diameters ranging from 0.020 to 0.250 inch [0.5 to 6.4 mm]. Special and oval shapes should have a minimum width of 0.020 inch [0.5 mm] and a major-to-minor-axis ratio of 3:1. Over 100 holes per machine stroke are practical. The same tooling can produce different sizes of holes within a modest range by adjusting the feed, voltage, and other parameters (see figure 11.10-2). A typical case was the simultaneous drilling of sixteen 0.050-inch [1.27 mm] diameter holes in cast Udimet 700 nickel alloy. The holes were 9-inches [229 mm] deep in the center of 0.150-inch [3.8 mm] thick airfoil walls. The drilling rate was 0.001 inch per second [0.025 mm/s] using a 10 percent sulfuric acid electrolyte.

TABLE 11.10-1 Some Materials that Have Been Drilled Using STEM™

304 Stainless steel	Incoloy alloy 825
321 Stainless steel	Rene 41
414 Stainless steel	Rene 80
4130 Alloy steel	Rene 95
4340 Alloy steel	Rene 100
M2 Tool steel	Ti-6Al-4V
DCM	Ti-6Al-2Sn-4Zr-2Mo
Stellite	Ti-8Al-1Mo-1V
Udimet 500	Haynes alloy 25 (L605)
Udimet 700	Haynes alloy 188
Udimet 710	HS-31 (X-40)
Inconel alloy 718	Hastelloy alloy C
IN-100	Hastelloy alloy X
IN-102	Greek Ascoloy
Inconel alloy 625	SEL 15
IN-738	TZM Molybdenum
Inconel alloy X-750	

11.10 Shaped Tube Electrolytic Machining—STEM™

Operating Parameters

TABLE 11.10–2 Typical Values for STEM™ Operating Parameters

Power supply	
type:	Direct current
voltage:	5 to 15 V
forward on time:	3 to 20 s
reverse time:	0.2 to 0.4 s
Electrolyte	
type:	H_2SO_4
concentration:	6 to 15% volume
temperature:	90° to 110°F [32° to 43°C]
pressure:	10 to 45 psi [69 to 310 kPa]
metal content:	8 oz/gal max. [6 g/L max.]
flow rate:	1.2 to 9.1 in^3/min [20 to 150 cm^3/min]
Feed rate:	0.030 to 0.080 in/min [0.76 to 2.0 mm/min]
Hole diameter:	0.02 to 0.25 inch [0.50 to 6.4 mm]
Bare electrode, OD.	See figures 11.10–2 to 11.10–4
Amperes per hole:	1 to 40 A
Holes per stroke:	1 to 100
Hole length:	Up to 24 inches [up to 610 mm]
Hole length-to-diameter ratio	Up to 300:1
Hole tolerance on diameter:	±5%
Hole tolerance, straightness:	0.0015 in/in [0.0015 mm/mm]
Surface roughness, R_a:	32 to 125 μin [0.8 to 3.2 μm]

NOTES: Electrolyte concentration below 10% reduces attack on tube insulation.

Hole size and roughness increases with increasing electrolyte contamination levels.

Reverse polarity is frequently at lower voltages (typically 4 to 5 V) than the forward voltages.

Material Removal Rates and Tolerances

Drilling penetration rates are typically 0.001 inch per second [0.025 mm/s] but can range from 0.0007 to 0.0025 inch per second [0.018 to 0.064 mm/s]. Several dozen holes have been drilled simultaneously, with tooling or setup costs being the practical limit. Runout is typically 0.0015 inch per inch [0.0015 mm/mm]; however, 0.001 inch per inch [0.001 mm/mm] can be achieved. Diameter tolerance is typically ±0.0015 inch [±0.038 mm] for hole diameters under 0.10 inch [2.5 mm] and plus or minus 10 percent for larger diameters. The material removal rates are governed by Faraday's laws (see section 11.5) and are limited by the current-carrying capacity of the tube and the boiling point of the electrolyte.

Surface Technology

Surface roughness in the holes ranges from 32 to 125 microinches R_a [0.8 to 3.2 μm]. There is no stress introduced into the surface. The electrolyte must be compatible with the metallurgical state of the workpiece to prevent intergranular attack or selective-etch pitting. The natural radiusing action of electrolytic machining eliminates all burrs. Close control of the electrolyte flow and degree of metal-ion contamination is required for quality assurance. Monitoring the current during operation can provide an early warning of size deviation.

Equipment and Tools

The STEM™ process equipment is available from the General Electric Company, Cincinnati, Ohio 45216. The equipment includes controls, tanks, pumps, and so on, and enclosures, ventilation and plastic components to protect the operator from the electrified and corrosive environment. Several equipment sizes are available to accomplish multiple drilling up to 24-inches [610 mm] deep. The tubes or "drills" are usually made from high quality titanium with acid-resisting organic coatings to provide insulation. Carbide locators withstand the environment of machining.

Machining Characteristics

Corrosion protection is required for equipment adjacent to STEM™ installations. Special tooling is required for through-hole drilling so that electrolyte pressure is not lost upon breakthrough. Careful straightening of the tubes is essential, as is end preparation and adhesion of the insulation.

SELECTED DATA

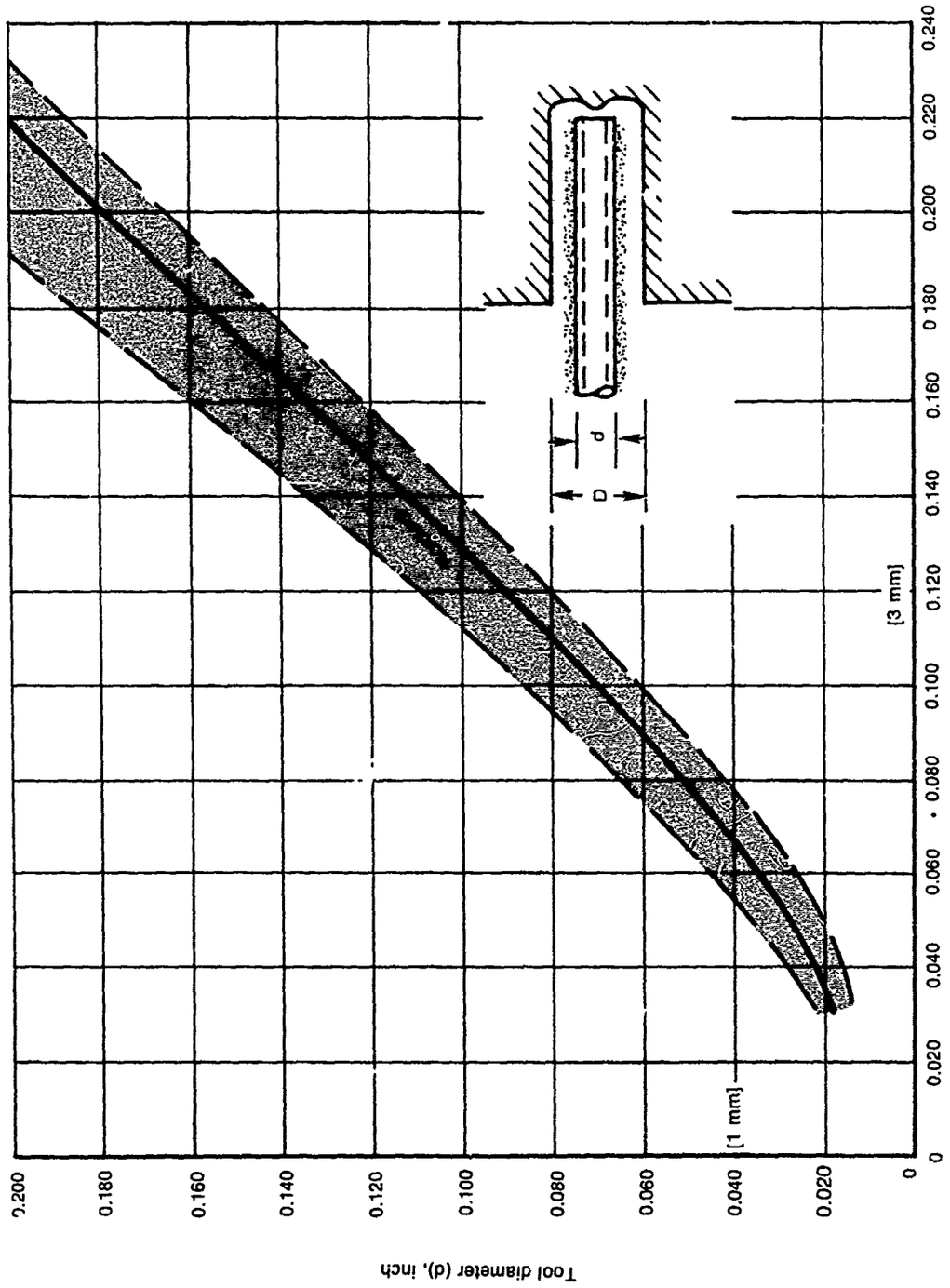


Figure 11.10–2 Tool diameter versus hole diameter for STEM™ drilling. Shaded area indicates hole sizes readily attainable with a particular diameter tool by varying the other operating parameters.

11.10 Shaped Tube Electrolytic Machining—STEM™

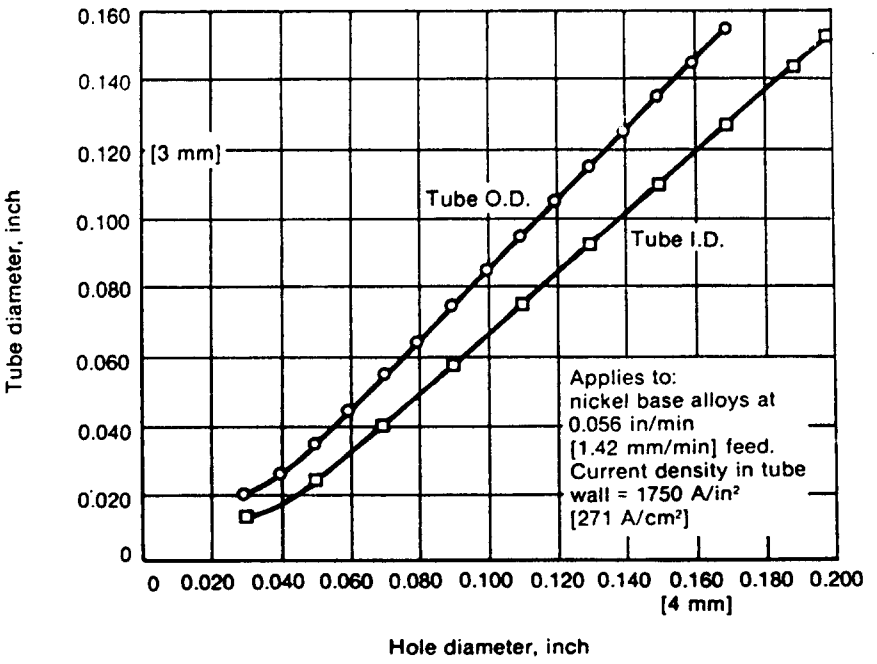


Figure 11.10–3 Tube diameter versus hole diameter for STEM™ drilling nickel base alloys. (C. Jackson and R. D. Olson, Shaped tube electrolytic machining, Technical paper MR69-109, Society of Manufacturing Engineers, Dearborn, MI, 1969, p. 10)

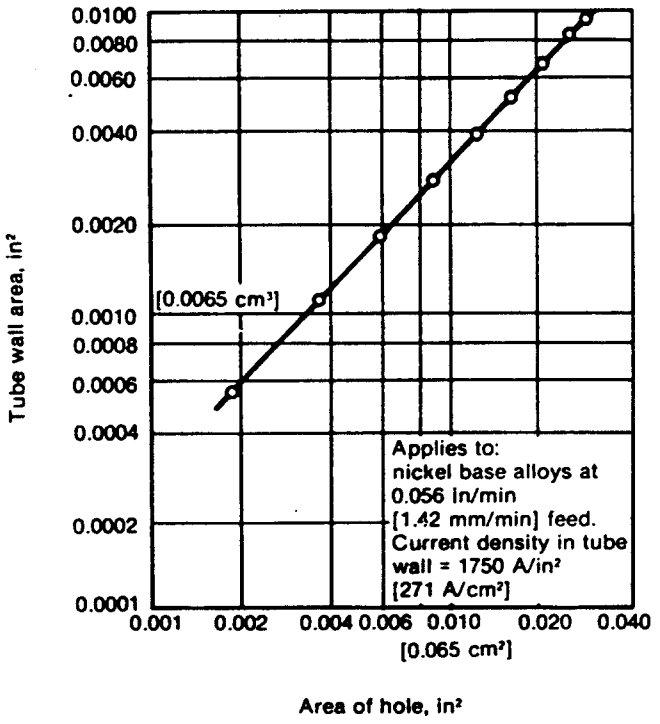


Figure 11.10–4 Tube wall area versus hole area for STEM™ drilling nickel base alloys. (C. Jackson and R. D. Olson, p. 10)

SPECIFIC APPLICATIONS DATA

TABLE 11.10–3 Specific Applications Data for STEM™

OPERATING PARAMETER	WORK MATERIAL						
	304 stainless steel	Udimet 700	Udimet 700	Inconel alloy 718	Rene 95	Ti-8Al-1Mo-1V	L605 (Haynes alloy 25)
Electrolyte							
type	H_2SO_4	H_2SO_4	H_2SO_4	H_2SO_4	H_2SO_4	HCl	H_2SO_4
concentration, % vol.	10	10	8	9–10	10	5.0 ±0.5	10
temperature, °F	90	100 ±2	95	100 ±2	100	100 ±5	100
pressure, psi	10	40	10 est.	25	22	45	10
metal content, g/L		2	2	3.0–6.5	4	none	
flow rate, cm^3/min		100	60	115 ±5	330	20	
Voltage, dc volts	10	6	10	7.4–7.8	6.5	13.5	6
Forward on time, s	8	7	8	10	10	10	3
Reverse time, s	0.3	0.1	0.3	0.3	0.3	0.3	0.3
Feed rate, in^3/min	0.060	0.050	0.050	0.050	0.050	0.070 ±0.003	0.0042
Hole diameter, in	0.02	0.050	0.120	0.05	0.124	0.060	0.025 ±0.003
Bare electrode, OD, in	0.015	0.035	0.090	0.035	0.107	0.045	0.017
Amperes per hole, A	1	1	8	2 max.	7.5	4.3	0.5
Holes per stroke	1	16	8	6	1	3	30
Hole length, in	6	9	2.5	4.0	1	8	0.030
Hole length-to-diameter ratio	300	180	21	80	20	134	1.2
Hole tolerance on diameter, in	±0.002	±0.0025			±0.002	±0.001	
Hole straightness, in/in		0.001					
Surface roughness, μin R_o					100–130	130–150	

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SECTION 12

THERMAL NONTRADITIONAL MACHINING OPERATIONS

12.1 Electron Beam Machining—EBM 12-3
12.2 Electrical Discharge Grinding—EDG 12-11
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Electron Beam Machining—EBM 12.1

PROCESS SUMMARY

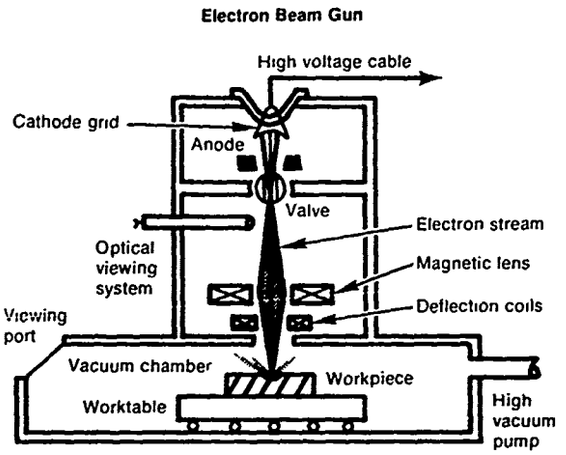


Figure 12.1-1 EBM schematic.

Principles

Electron beam machining (EBM) removes material by melting and vaporizing the workpiece at the point of impingement of a focused stream of high-velocity electrons (see figure 12.1-1). To eliminate scattering of the beam of electrons by contact with gas molecules, the work is done in a high-vacuum chamber. Electrons emanate from a triode electron beam gun and are accelerated to three-fourths the speed of light at the anode. The collision of the electrons with the workpiece immediately translates their kinetic energy into thermal energy. The low-inertia beam can be simply controlled by electromagnetic fields. Magnetic lenses focus the electron beam on the workpiece, where a 0.001-inch [0.025 mm] diameter spot can attain an energy density of up to 10^9 watts per square inch [1.55 x 10^8 W/cm^2] to melt and vaporize any material. The extremely fast response time of the beam is an excellent companion for three-dimensional computer control of beam deflection, beam focus, beam intensity and workpiece motion. View ports and optical tracking systems help guide the beam or the workpiece. Deflection coils permit magnetic control and programming of the beam to any desired pattern over a small area—about 1/4-inch [6.4 mm] square.

Practical Applications

The power densities available in EBM will vaporize any known material (see examples, table 12.1-2). This permits a wide range of processing possibilities, as shown in figure 12.1-2. Micromachining of thin materials, engraving and hole drilling are the principal applications for EBM. The hole depth-to-diameter ratio can reach 100:1 with multiple pulses. The capability for machining microholes and narrow slots with high precision in a short time in any material also permits the production of unique designs. Figures 12.1-3 and 12.1-4 show perforation ranges and rates for EBM of steels and nickel alloys. The absence of mechanical contact and the suitability for automatic control enhance the process capabilities, but the necessity to work in a vacuum lengthens the floor-to-floor cycle time. One application placed 400,000 holes 80 microinches [2 μm] in diameter in each square inch of a 0.001-inch [0.025 mm] thick foil. Another application incorporates the drilling of holes approximately 0.020 inch [0.50 mm] in diameter in 0.250-inch [6.4 mm] thick material at speeds several times faster than for EDM or ECM. Metering orifices, rough wire dies and spinnerette holes are other applications.

Operating Parameters

TABLE 12.1-1 Typical Values for EBM Operating Parameters

Accelerating voltage:	50 to 150 kV
Beam current:	100 to 1,000 μA
Power:	0.5 to 60 kW
Pulse time:	4 to 64,000 μs
Pulse frequency:	0.1 to 16,000 Hz
Vacuum:	10^{-2} to 10^{-4} mm Mercury
Beam spot size minimum:	0.0005 to 0.001 inch [0.013 to 0.025 mm]
Beam deflection range:	0.25-inch [6.4 mm] square
Beam intensity:	10^6 to 10^{10} W/in^2 [1.55 x 10^5 to 1.55 x 10^9 W/cm^2]
Depth of cut:	Up to 0.25 inch [6.4 mm]
Narrowest cut:	0.001 inch in 0.001-inch thick metal [0.025 mm in 0.025-mm thick metal]
Hole range, diameter:	0.001 inch [0.025 mm] in 0.0007-inch [0.020 mm] thickness 0.040 inch [1 mm] in 0.20-inch [5 mm] thickness
Hole taper:	1° to 2° typical
Hole angle to surface:	20° to 90°
Cutting speed:	See tables 12.1-3 and 12.1-4
Material removal rates:	Up to 0.0024 in^3/s [40 mm^3/s], see figure 12.1-5
Penetration rates:	Up to 0.010 in/s [0.25 mm/s]
Perforation rates:	Up to 5,000 holes/second (if part can be traversed rapidly)
Tolerances:	±0.001 inch [0.025 mm] on 0.125-inch [3.2 mm] diameter, see figure 12.1-6 ±0.00005 inch [0.0013 mm] on 0.0005-inch [0.013 mm] diameter ±0.001 inch [0.025 mm] typical and ±0.0002 inch [0.005 mm] attainable, 10% otherwise

12.1 Electron Beam Machining—EBM

Material Removal Rates and Tolerances

The thermal properties of the work material and the power level of the EBM unit dictate the material removal rates. Tungsten can be machined at a rate of 0.92 x 10^{-4} cubic inch per second (15 x 10^{-4} cm^3/s) with one kilowatt of power, while aluminum can be machined at a rate of 0.24 x 10^{-3} cubic inch per second (3.9 x 10^{-3} cm^3/s) with the same power level, as shown in figure 12.1-5. Typical tolerances are about 10 percent of the slot width or hole diameter, as shown in figure 12.1-6. The taper present in slots and holes limits the depth-to-width ratio. With computer control of the pulsed beam and integrated workpiece motion, hole drilling rates up to 5,000 holes per second can be attained in thin materials, including ceramics.

Surface Technology

Estimates of surface roughness for the small holes and cuts are in the neighborhood of 40 microinches R_a (1 μm). The short bursts of the beam limit the extent of the heat-affected zone; however, there is always a thin layer of recast or heat-affected material on the cut surface. Heat-affected material up to 0.010-inch (0.25 mm) thick has been observed. This material can be detrimental to the structural integrity of highly stressed components, and for such components, this material should be removed or modified.

Equipment and Tools

Machines for EBM are produced with capacities ranging from a few hundred watts to 60,000 watts with vacuum chambers of nominal or special volume—up to 20-by-27-foot (6 by 9 m) capacity. Special equipment can include room-size chambers with electron beam guns traveling over NC positioning tables. Optical scans and controls with as much as 40:1 magnification are available to utilize the precision capability of the small spot size, high beam power densities and low beam inertia. Simultaneous control of the beam and the work motion is common. Proper programming of the deflection beam, "flying spot" scanners and pulse controls can produce intricate geometric cuts in the workpiece.

Machining Characteristics

The "chips" from EBM are small dust particles or small beads formed from the solidified, expulsed molten material. Cleanliness efforts should be continuous. Cathode life declines at the higher power densities. Shielding of the secondary radiation is necessary for safety.

SELECTED DATA

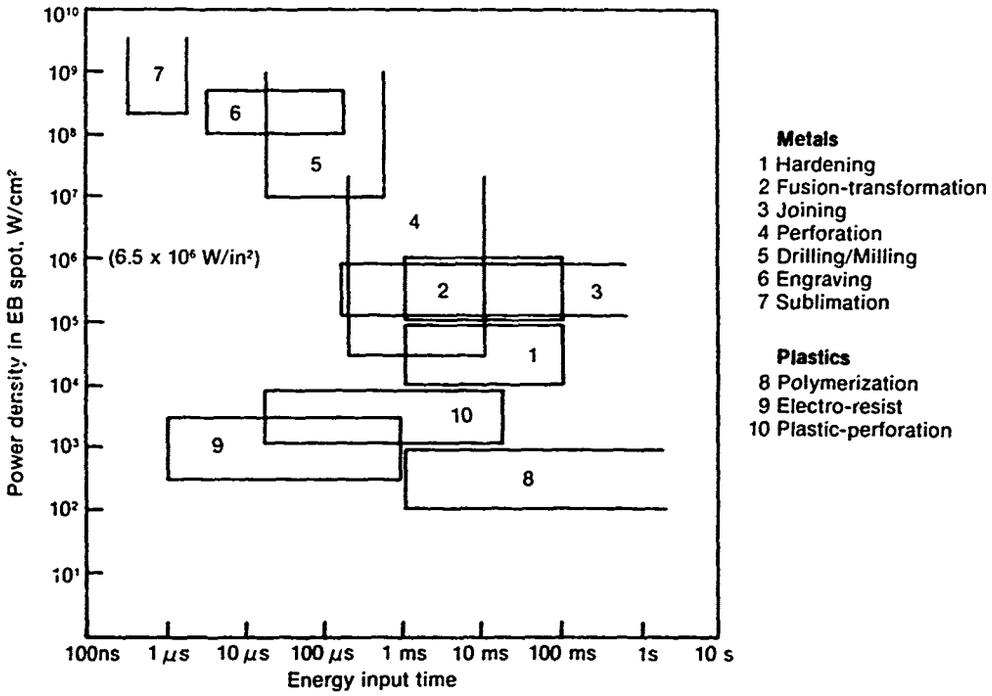


Figure 12.1–2 Application range of electron beams. Power density and time of impact are typical for the various techniques. (J. Drew, Electron beam drilling, *Influence of metallurgy on hole making operations*, Metals Park, OH: American Society for Metals, 1978, p. 115)

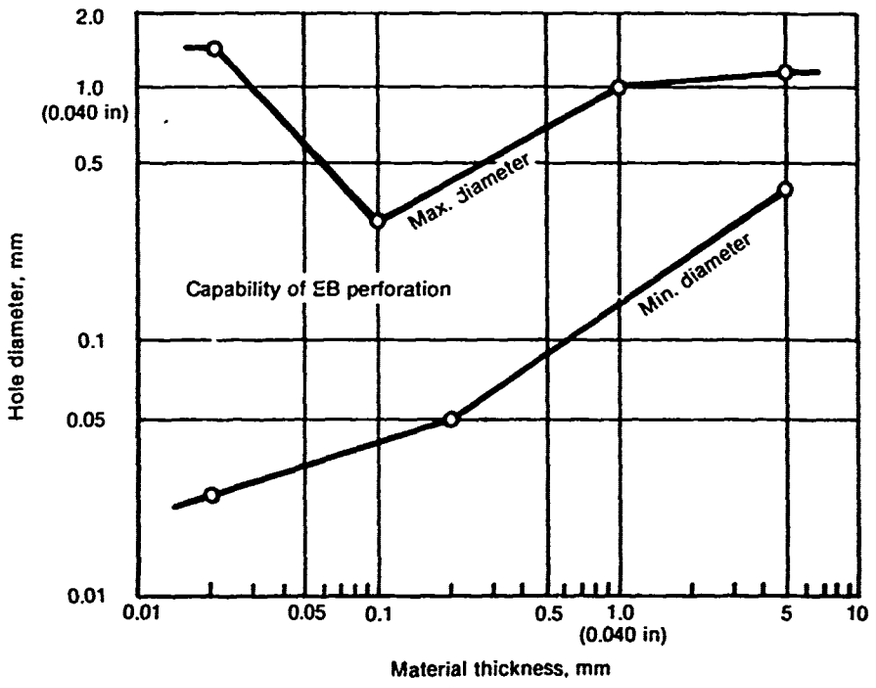


Figure 12.1–3 Range of EB perforation for steel and nickel alloys. (J. Drew, p. 118)

12.1 Electron Beam Machining—EBM

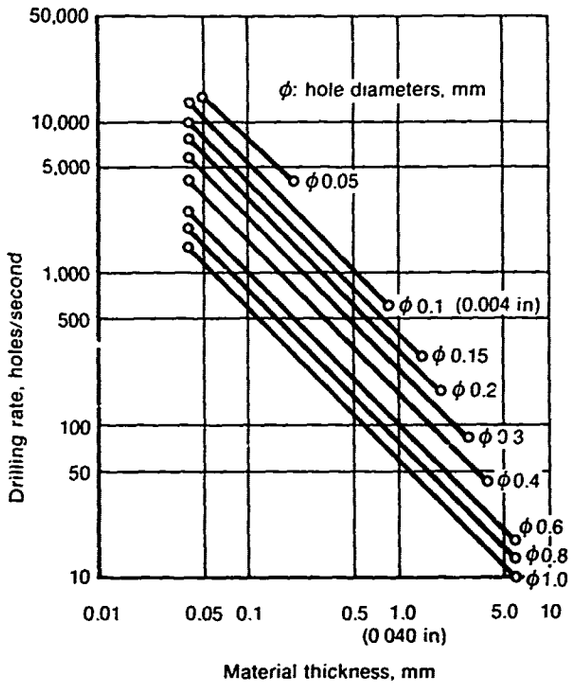


Figure 12.1–4 EB perforation rate for steel and nickel alloys. (J. Drew, p. 119)

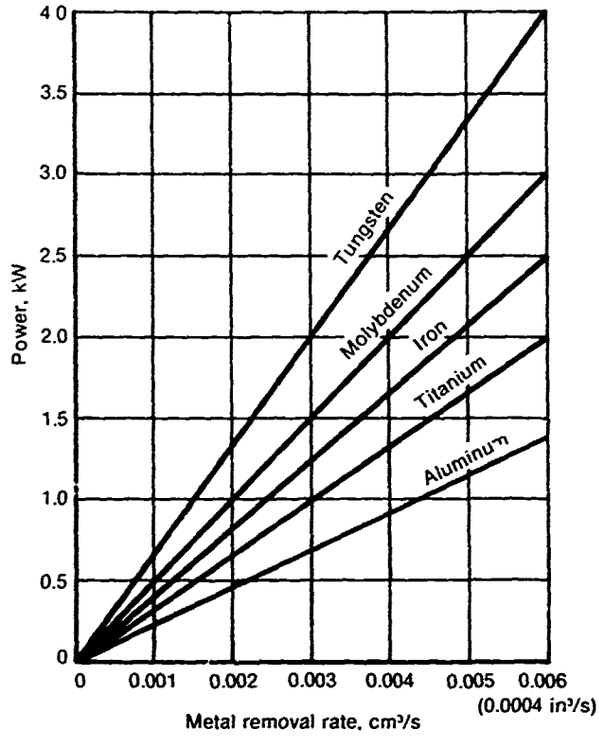


Figure 12.1–5 Metal removal rates versus power, assuming 15 percent cutting efficiency. (R. K. Springborn, ed., *Non-traditional machining processes*, Dearborn, MI: American Society of Tool and Manufacturing Engineers, 1967, p. 141)

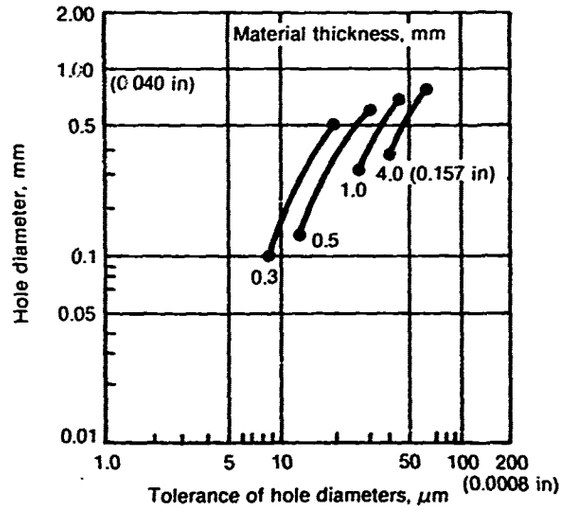


Figure 12.1–6 Hole tolerances variation with hole size and material thickness. Generally, deeper holes require wider tolerances. (J. Drew, Electron beam tackles tough machining jobs, *Machine Design* 48 (February 26, 1976), p. 96)

TABLE 12.1–2 Physical Thermal Properties of Various Materials

PROPERTY	MATERIAL				
	Aluminum	Titanium	Molybdenum	Tungsten	Iron
Melting temperature, °C	660	1,668	2,610	3,410	1,536
Boiling temperature, °C	2,450	3,260	5,560	5,930	3,000
Specific heat, cal/g/°C	0.215	0.126	0.061	0.032	0.11
Heat of fusion, cal/g	94.6	36.7	70.0	44.0	65.0
Heat of vaporization, cal/g	2,517.6	2,223.4	1,340	1,005.9	1,514.8
Specific energy to vaporize, joules/cm³	3.54×10^4	5.07×10^4	7.46×10^4	1.0×10^5	6.28×10^4
Power to vaporize* (ratio to aluminum)	100	150	220	290	180

*Relative power to remove equal volumes in equal time.

TABLE 12.1–3 Holes Drilled by EBM in Various Materials

WORK MATERIAL	WORKPIECE THICKNESS		HOLE DIAMETER		DRILLING SPEED	ACCELERATING VOLTAGE	AVERAGE BEAM CURRENT	PULSE WIDTH	PULSE FREQUENCY
	in	[illegible]	in	[illegible]	s	kV	μA	μs	Hz
400 Series stainless steel	0.010	[illegible]	0.0005	[illegible]	<1	130	60	4	3,000
Alumina Al_2O_3	0.030	[illegible]	0.012	[illegible]	30	125	60	80	50
Tungsten	0.010	[illegible]	0.001	[illegible]	<1	140	50	20	50
90-10 Tantalum-tungsten	0.040	[illegible]	0.005	[illegible]	<1	140	100	80	50
90-10 Tantalum-tungsten	0.080	[illegible]	0.005	[illegible]	10	140	100	80	50
90-10 Tantalum-tungsten	0.100	[illegible]	0.005	[illegible]	10	140	100	80	50
Stainless steel	0.040	[illegible]	0.005	[illegible]	<1	140	100	80	50
Stainless steel	0.080	[illegible]	0.005	[illegible]	10	140	100	80	50
Stainless steel	0.100	[illegible]	0.005	[illegible]	10	140	100	80	50
Aluminum	0.100	[illegible]	0.005	[illegible]	10	140	100	80	50
Tungsten	0.016	[illegible]	0.003	[illegible]	<1	130	100	80	50
Quartz	0.125	[illegible]	0.001	[illegible]	<1	140	10	12	50

SOURCE: Adapted from R. K. Springborn, ed., p. 143.

NOTE: The main control parameters for shaping the hole are the pulse width for the depth of the hole, the beam current for the diameter of the hole and the power distribution within the beam as well as the position of the focus with respect to the workpiece.—J. Drew, Farrel Company.

12.1 Electron Beam Machining—EBM

TABLE 12.1–4 Slots Cut by EBM in Various Materials

WORK MATERIAL	WORKPIECE THICKNESS		SLOT DESCRIPTION AND/OR DIMENSIONS		TIME OF CUT OR RATE		ACCEL-ERATING VOLTAGE	AVERAGE BEAM	PULSE WIDTH	PULSE FRE-QUENCY
	in	mm	in	mm			kV	μA	s	Hz
Stainless steel	0.062	1.57	Rectangle: 0.008 by 0.250	Rectangle: 0.2 by 6.35	5 min	5 min	140	120	80	50
Hardened steel	0.125	3.18	Rectangle: 0.018 by 0.072	Rectangle: 0.46 by 1.83	10 min	10 min	140	150	80	50
Stainless steel	0.007	0.18	0.004 wide	0.10 wide	2 in/min	50 mm/min	130	50	80	50
Brass	0.010	0.25	0.004 wide	0.10 wide	2 in/min	50 mm/min	130	50	80	50
Stainless steel	0.002	0.050	0.002 wide	0.050 wide	4 in/min	100 mm/min	130	20	4	50
Alumina Al_2O_3	0.030	0.75	0.004 wide	0.10 wide	24 in/min	610 mm/min	150	200	80	200
Tungsten	0.002	0.050	0.001 wide	0.025 wide	7 in/min	178 mm/min	150	30	80	50

SOURCE: Adapted from R. K. Springborn, ed., p. 145.

SPECIFIC APPLICATIONS DATA

TABLE 12.1–5 Specific Applications Data for Electron Beam Machining

MATERIAL	CONFIGURATION PRODUCED	CUTTING SPEED OR TIME	ACCELERATING VOLTAGE kV	AVERAGE BEAM CURRENT μA	PULSE WIDTH μs	PULSE FREQUENCY Hz
Alumina 0.030-inch thick	0.012-inch dia. hole	30 s	125	60	80	50
Alumina wafers 0.010-inch thick	0.003-inch dia. hole	10 s	125	60	80	50
0.010-inch thick	0.004-inch wide slot	12 in/min	90	150	80	150
0.030-inch thick	0.004-inch wide slot	24 in/min	150	200	80	200
Ferrite wafers 0.010-inch thick	0.001-inch dia. holes	<1 s	140	25	5	50
Microdiodes scribing	Scribed to approx. 1 mil depth	Approx. 60 in/min	110	7	12	50
Mylar tape 0.0015-inch thick	Cut	4,615 in/min	110	600	—	Continuous
Quartz crystal 0.125-inch thick	0.001-inch exit dia.	<1 s	140	10	12	50
Sapphire crystal 0.026-inch thick	0.0025-inch dia. hole	<30 s	110	20	9	50
0.026-inch thick	0.0015-inch dia. hole, hole taper approx. 2°	<30 s	110	20	9	50
Silicon wafers 0.010-inch thick gold deposited	Scribed to 0.002-inch depth	5 in/min	130	70	4	3,000
Aluminum 0.100-inch thick	0.005-inch dia. hole	10 s	140	100	80	50
Aluminum, 5052 1/16-inch and 1/8-inch thick	Slotting	Manual	130	15	500	300
Copper (OFHC) 0.002-inch thick traveling wave tube grid	Cut	Approx. 1 min	130	50	2.5	25,000 (scanner)
Brass 0.010-inch thick	0.004-inch wide slot	2 in/min	130	50	80	50
Brass, foil grid 0.004-inch thick	Cut by flying spot scanner	Approx. 3 min	120	50	4	3,000
Steel, hardened 0.125-inch thick	Rectangle—0.018 by 0.072 inch	10 min	140	150	80	50
Steel, high speed tool 0.1875-inch thick	0.008-inch entrance width, 0.007-inch exit width, slot	—	120	30,000	50,000	3.3
Steel, drill	0.014-inch dia. hole	Approx. 3 min	140	200	80	50
Steel, plate 0.062-inch thick	Cut	15 in/min	150	9,000	2,100	330
0.040-inch thick	Cut	30 in/min	150	9,000	2,100	330
Steel, 304 stainless ¼-inch thick	Cut (reopening of welded container)	10 to 20 in/min	130	5,000	5,300	35
Steel, stainless (400 series) 0.010-inch thick	0.0005-inch dia. hole	<1 s	130	60	4	3,000
Steel, 410 stainless 0.250-inch thick	0.030-inch entrance width, 0.010-inch exit width, slot	—	150	7,000	1,000	3.3

TABLE 12.1-5—Continued

MATERIAL	CONFIGURATION PRODUCED	CUTTING SPEED OR TIME	ACCELERATING VOLTAGE kV	AVERAGE BEAM CURRENT μA	PULSE WIDTH μs	PULSE FREQUENCY Hz
Steel, stainless						
0 250-inch thick	0.020- to 0.040-inch dia. holes	3 min	145	4,000	2,100	12.5
0.040-inch thick	0.005-inch dia. hole	<1 s	140	100	80	50
0.080-inch thick	0.005-inch dia. hole	10 s	140	100	80	50
0.100-inch thick	0.005-inch dia. hole	10 s	140	100	80	50
0.062-inch thick	Rectangle—0.008 by 0.250 inch ±0.00025 inch	5 min	140	120	80	50
0.007-inch thick	0.004-inch wide slot	2 in/min	130	50	80	50
0.002-inch thick	0 002-inch wide slot	4 in/min	130	20	4	50
Hastelloy	0.200-inch dia. hole in 0.200-inch thick material	—	130	5,000	5,300	100
	0.100-inch dia. hole in 0.450-inch thick material	70 s	130	5,000	5,300	100
Molybdenum, shim						
0 010-inch thick	Less than 0.002-inch dia. holes on 0.003-inch centers	<1 s	140	20	20	50
Tantalum alloy (90Ta-10W)						
0.040-inch thick	0.005-inch dia. hole	<1 s	140	100	80	50
0 080-inch thick	0.005-inch dia. hole	10 s	140	100	80	50
0.100-inch thick	0.005-inch dia. hole	10 s	140	100	80	50
Tantalum, 100A						
thin film resistor	Manual cut	—	100	20	9	1,000
Tungsten						
0.010-inch thick	0.001-inch dia. hole	<1 s	140	50	20	50
0.016-inch thick	0.003-inch dia. hole	<1 s	130	100	80	50
0.002-inch thick	0.001-inch wide slot	7 in/min	150	30	80	50

PROCESS SUMMARY

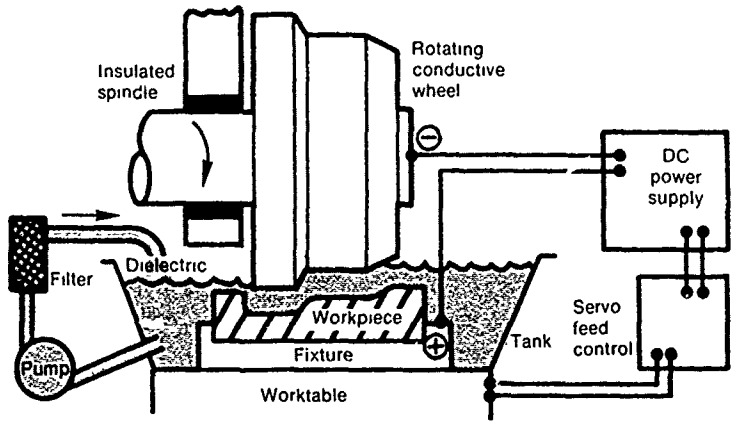


Figure 12.2–1 EDG schematic.

Principles

Electrical discharge grinding (EDG) is the removal of a conductive material by rapid, repetitive spark discharges between a rotating t ·l and the workpiece, which are separated by a flowing c· lectric fluid (see figure 12.2-1). (EDG is similar to EDM except the electrode is in the form of a grinding wheel and the current is usually lower.) The spark gap is servo controlled. The insulated wheel and work table are connected to the direct-current pulse generator. A positive charge on the workpiece is "standard." Higher currents produce faster cutting, rougher finishes and deeper heat-affected zones in the workpiece. Wheel wear depends upon current density, work material, wheel material, dielectric and sharpness of corner details.

Practical Applications

EDG provides greater accuracy in cutting hard materials such as carbide form tools, hardened gear racks or tungsten carbide throwaway bits, even though its cutting rates are low. Lamination die grinding in the hardened state is a frequent use of EDG. The absence of significant cutting forces permits the grinding of fragile shapes or closely spaced, thin slots in any conductive material. Cast irons usually are not electrical-discharge-ground because the sand inclusions can damage the grinding wheel.

Operating Parameters

TABLE 12.2–1 Typical Values for EDG Operating Parameters

Power supply.	
type:	Direct current with pulse control
voltage:	30 to 400 V
frequency:	200 Hz to 500 kHz
current:	0.5 to 200 A
Wheel	
type:	Graphite or sometimes brass
speed:	100 to 600 fpm [30 to 180 m/min]
Dielectric:	Filtered hydrocarbon oil
Spark gap:	0.0005 to 0.003 inch [0.013 to 0.076 mm]

Material Removal Rates and Tolerances

Material removal rates range from 0.01 to 0.15 cubic inch per hour [0.16 to 2.45 cm^3/hr], with the higher figures accompanied by surface roughness in the 63- to 125-microinch R_a [1.6 to 3.2 μm] range. Corner radius depends upon overcut values used and ranges from 0.0005 to 0 005 inch

12.2 Electrical Discharge Grinding—EDG

(0.013 to 0.13 mm). Tolerances to ±0.0002 inch (±0.005 mm) are normal, with ±0.000050 inch (±0.0013 mm) achievable.

Surface Technology

Surface roughness values decrease with an increase in spark frequency and are typically 16 to 125 microinches R_a (0.4 to 3.2 μm). The melting, vapo[illegible]g and resolidification of the surface of the workpiece l[illegible]s a heat-affected zone that can be from a few ten[illegible] sandths- to a few thousandths-inch deep. Hardness [illegible]erations occur which also affect the material properties. Components intended for high-stress applications should have these heat-affected layers removed or modified to ensure the best surface integrity.

TABLE 12.2-2 EDG Material Removal Rates versus Surface Roughness

MATERIAL REMOVAL RATE		SURFACE ROUGHNESS, R_a	
in³/hr	cm³/hr	μin	μm
0.05	0.82	125	3.2
0.03	0.49	63	1.6
0.002	0.03	16	0.4

Equipment

Equipment for EDG is available in a range of sizes. Systems are equipped with variable speed drive, insulated wheel spindles and a servomechanism to control the table speed.

Machining Characteristics

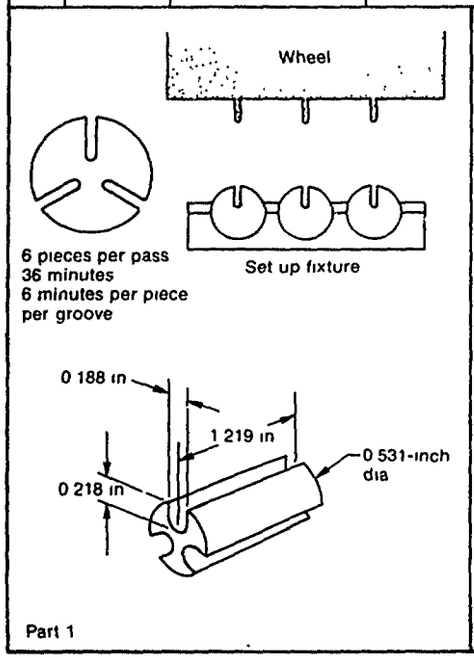
Grinding action is nonexistent. Wheel wear occurs from the spark discharge. The wear ratio ranges from 100:1 to 0.1:1 with an average of 3:1

$$\text{volumetric wear ratio} = \frac{\text{volume of work removed}}{\text{volume of wheel consumed}}$$

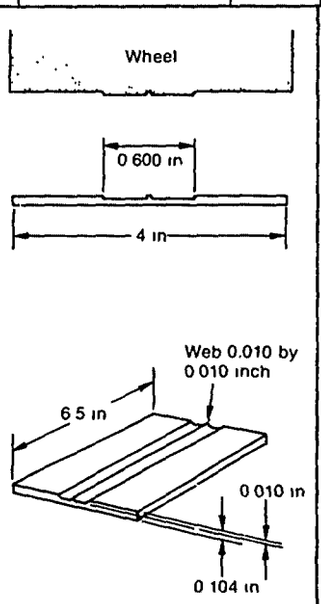
It is necessary to redress the wheel frequently if sharp radii are desired. Sharp radii also contribute to more rapid wheel wear than do round or flat shapes. About one-half of the wear ratio can be attributed to redressing. The dielectric fluid must be inserted between the wheel and the workpiece; consequently, the contact area is usually submerged in dielectric.

TABLE 12.2–3 Specific Applications Data for Electrical Discharge Grinding of Stainless Steels

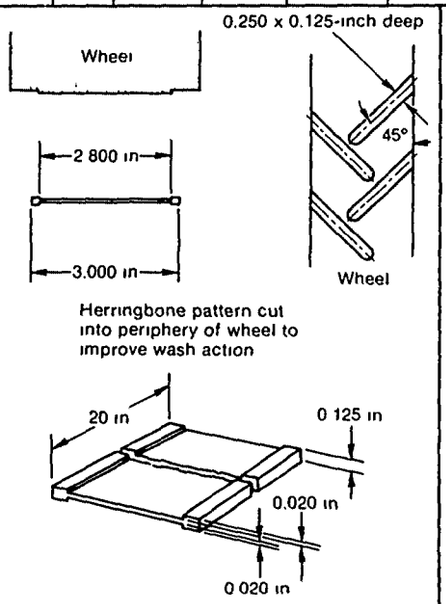
WORK					OPERATING CONDITIONS					RESULTS				
Part No.	Type of Stainless Steel	Description of Workpiece	Shape Produced	Dimensions of Shape Produced	Speed* rpm	Volts	Current A	Capacitance mfd	Pulse Frequency kHz	Grinding Rate in³/hr	Cutting Time min	Volume Wear Ratio	Overcut in/side	Surface Roughness μin R_a
1	303	Rod, 0.531-inch dia. by 1.219-inch long	3 grooves	0.188-inch wide, 0.218-inch deep; full-radius bottom	20	70	10	6	32	0.470	6	3:1	0.0017	200
2	304	Strip, 0.104 by 4.000 by 6.500 inch	Rib	0.600-inch wide, 0.010-inch deep; central web 0.010-inch wide	20	70	0.5	0.5	32	0 06	44	3·1	0.001	60
3	304	Strip, 0.125 by 3 by 20 inch	2 grooves	2.800-inch wide, 0.020-inch deep	20	70	2	2	130	0.156	400	6.1	0.001	60
4	304	Hexagonal tubing, 2.25-by-0.050-inch wall	Face, step-cut end	Step, 0.187-inch deep	34	80	8	2	32	—	30	—	0 00 i	125



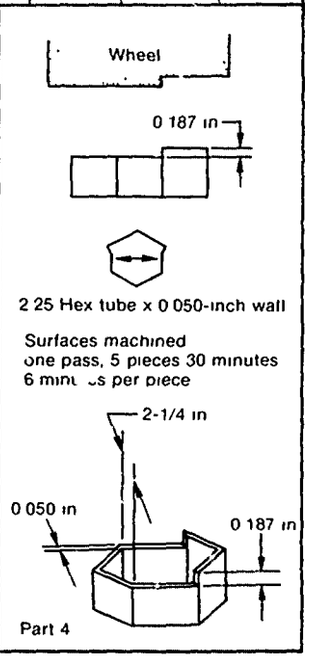
Part 1



Part 2



Part 3



Part 4

*Wheel diameter is 12 inches.

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Electrical Discharge Machining—EDM 12.3

PROCESS SUMMARY

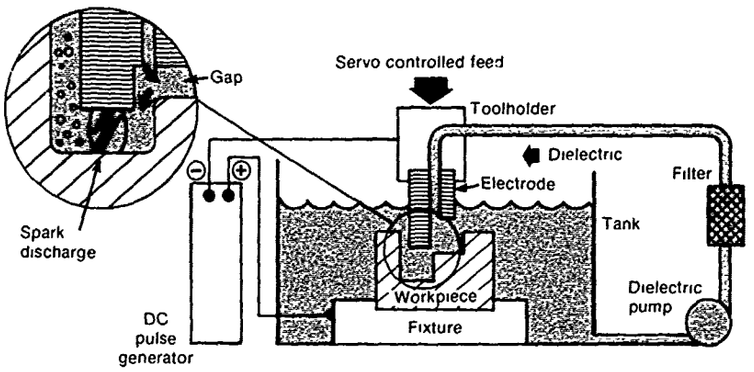


Figure 12.3-1 EDM schematic.

Principles

Electrical discharge machining (EDM) removes electrically conductive material by means of rapid, repetitive spark discharges from a pulsating direct-current power supply with dielectric flowing between the workpiece and the tool (see figure 12.3-1). The shaped tool (electrode) is fed into the workpiece under servo control. A spark discharge then breaks down the dielectric fluid. The frequency and energy per spark are set and controlled with a direct-current power source. The servo control maintains a constant gap between the tool and the workpiece while advancing the electrode. The dielectric oil cools and flushes out the vaporized and condensed material while reestablishing insulation in the gap. Surface roughness decreases with increased frequency and reduced current. Material removal rate, surface roughness and overcut all increase with a current increase or with a frequency decrease (or longer "on" time cycles). Electrode materials frequently used are brass, copper, copper-tungsten, tungsten wire and graphite Small spark gaps are associated with close tolerance control and slower cutting rates. Erosion occurs on the tool as well as on the workpiece, with wear ratios depending on spark wave-shape from the power source, electrode material and workpiece material. A nearly "no wear" combination of operating parameters can be found for electrical discharge machining of some steels when using reverse polarity, as opposed to "standard" polarity (positive on the workpiece).

Practical Applications

EDM cuts any electrically conductive material regardless of its hardness and is particularly adapted for machining irregular slots or cavities. The scope of EDM applications extends from 0.002-inch [0.050 mm] diameter holes to 50 ton [45 metric tons] automotive die cavities. Because there is no physical contact, delicate structures can be cut successfully. Cutting is three-dimensional as the shaped electrode is fed into the workpiece. Because the sparks focus first on peaks and corners, burr-free cutting occurs. Multiple electrodes, automatic dressing, automatic positioners and NC motion control all contribute to electrical discharge machining's versatility. Tool and die work is a frequent EDM application, but mass production and even transfer-line applications exist. EDM production of small and/or shaped holes at shallow angles to the workpiece surface is commonplace. Narrow slots (0.002- to 0.012-inch [0.050 to 0.30 mm] wide), honeycomb cores and fragile parts can be cut in high-strength and high-hardness materials.

Operating Parameters

See table 12.3-1.

Material Removal Rates and Tolerances

Feed rates and material removal rates range from 0.00036 to 0.04 cubic inch per hour per ampere [0.0059 to 0.65 $cm^3/hr/A$]. Corner radii to 1/64 inch [0.4 mm] are common. Production tolerance to ±0.001 inch [±0.025 mm] is normal; tolerances of ±0.0002 inch [±0.005 mm] are repeatable with careful selection or development of cutting conditions. The recast layer can be controlled and is repeatable to a few ten-thousandths inch.

Material removal rates, surface roughness, recast layer and heat-affected zones all increase as spark intensity increases, see table 12.3-3.

Electrode erosion is expressed as wear ratio as follows (see also figure 12.3-19):

$$\text{volumetric wear ratio} = \frac{\text{volume of work removed}}{\text{volume of electrode consumed}}$$

or

$$\text{linear wear ratio} = \frac{\text{depth of cut}}{\text{length of electrode consumed}}$$

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Corner radii are controlled by the spark length, while taper is controlled by the amount of cutting debris in the arc gap or fluid.

TABLE 12.3–1 Typical Values for EDM Operating Parameters

INDEPENDENTLY CONTROLLABLE PARAMETERS	
Open circuit voltage:	50 to 300 V
Frequency.	50 Hz to 500 kHz or equivalent duty-cycle setting of on and off times per pulse
Dielectric type:	Hydrocarbon (petroleum) oils, deionized water, kerosene, gas (dry) (see table 12.3–10)
Dielectric flow pressure.	28-inch [711 mm] vacuum to 70 psi [482 kPa] pressure
Electrode materials:	Graphite, copper, brass, zinc-tin, steel, copper-tungsten, copper-graphite, silver-tungsten, tungsten
Servo drive gap sensitivity control:	Gaps: 0.0005 to 0.005 inch [0.013 to 0.13 mm]
Capacitance:	(on some style machines) from trial cuts
Polarity:	"Standard" is positive on workpiece, negative on electrode (see table 12.3–8)
DEPENDENT VARIABLES AND RESULTS	
Average current:	0.1 to 500 A (A few large machines use multiple 500 A power packs, with separate leads.)
Spark gap:	0.0005 to 0.005 inch [0.013 to 0.13 mm]
Overcut:	0.0002 to 0.020 inch/side [0.005 to 0.50 mm]
Material removal rate:	0.003 to 1.5 in^3/hr [0.05 to 24.6 cm^3/hr]
Wear ratio (ratio of workpiece erosion to electrode erosion):	0.5:1 to 100:1 (see table 12.3–12)
Surface roughness:	8 to 250 microinches R_a [0.2 to 6.3 μm]
Depth of recast plus heat-affected zone:	0.0001 to 0.005 inch [0.0025 to 0.13 mm]
Corner radius:	0.001 inch [0.025 mm] or equal to overcut
Taper	0.0005 to 0.005 inch/inch/side [0.0005 to 0.005 mm/mm/side]. With proper tooling, taper can be eliminated.

Surface Technology

The surface texture is a series of overlapping, small craters that increase in size with increasing spark energy and/or lower spark frequency. Recast and heat-affected layers occur on all materials and range from 0.0001- to 0.005-inch [0.002 to 0.13 mm] deep. These layers should be removed or modified on critical or fatigue-sensitive surfaces. Surface roughness is typically in the 63- to 125-microinch R_a [1.6 to 3.2 μm] range. Surface roughness from rough cuts can range up to 500 microinches R_a [12.5 μm], and more costly, deluxe methods can attain 2 to 4 microinches R_a [0.05 to 0.1 μm]. Surface residual stress is shallow (under 0.001 inch [0.025 mm]) but may be a high percent of tensile strength. The fatigue strength of EDM surfaces without post-treatment usually is severely reduced.

Equipment

EDM equipment is available in a wide range of sizes from a bench model with a few amperes capacity to 13-by-18-foot [4 by 5.5 m] die sinkers with 5,000-ampere capacity (made up from multiple 500-ampere power packs). Automatic or NC controls are common. Automatic feed, interchangeable electrode holders and rotary-turret electrode holders are available to aid electrode changing and automation of the EDM process. Multiple electrodes and multi-lead power supplies enhance the productivity of many equipment types. Integrated systems are the usual order; thus, EDM machines can be placed almost anywhere in the normal shop. Fume vents are recommended, and tooling should provide a means for venting the liberated gases. The pulse power supply usually contains full control of "on and off" times for each discharge, as well as full control of the discharge energy.

The "grinding" mode of EDM is covered in section 12.2 on EDG. Section 12.5 on EDWC covers the wire cutting EDM operations. Orbital or planetary erosion is a recent addition to EDM capabilities. This method makes possible the almost constant enlargement of a die cavity of geometrically difficult contour with simple electrodes. Electrode motions range from simple orbital movement to complex combinations of vertical, eccentric and orbital motions, as shown in figure 12.3–2.

Machining Characteristics

High quality output depends upon rigid machine tools and fixturing for close gap control via the servomechanism which controls the electrode movement.

Good safety practice makes it desirable to operate with the spark fully submerged in the dielectric. Gas and fumes generated should be carefully vented. Good hygiene, thorough washing by the machine operator and the use of a moisturizing cream can eliminate skin irritations caused by the dielectric oils.

Figure 12.3-2 Orbital or planetary erosion motions in EDM. **S** represents feed direction. (Courtesy of Agietron Corporation)

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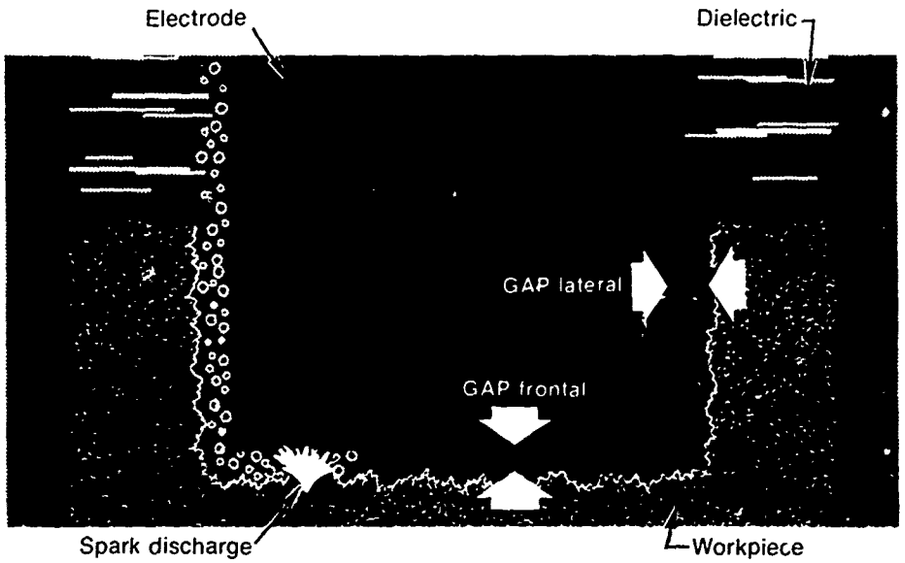
SELECTED DATA

There are many combinations of EDM operating parameters that will remove material from conductive workpieces. Experience with particular equipment and/or systems plus a limited number of test points on particular electrode-material/workpiece-material combinations will provide the operator with reference points for improved estimating and operating efficiency. Most equipment manufacturers are supplying approved data for their installations These data frequently are measured under "standard" conditions.[1] In practical application, deviations from "standard" might result from the use of different materials, dielectric fluids, or product forms or from different levels of operator experience.

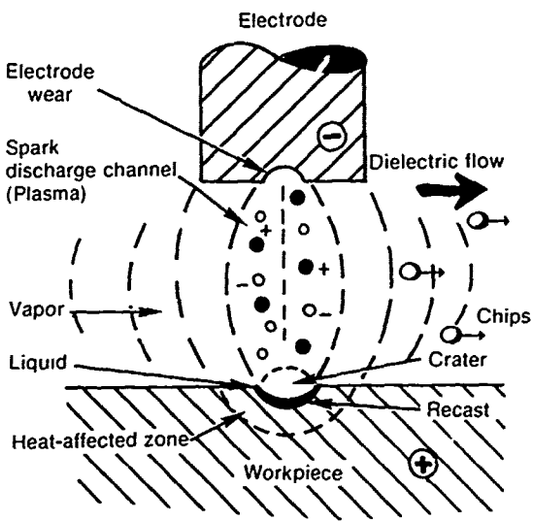
The steps in table 12.3-2 are recommended as one logical sequence for selecting EDM operating parameters. Supporting data come from the other figures and tables in accordance with the terms as explained in figure 12.3-3.

[1]Swiss standard 37550 and a German recommendation VDI 3400 are in existence circa 1979.

Generalized Cavity Cut



Simplified Spark Discharge



Simplified Voltage and Current Traces

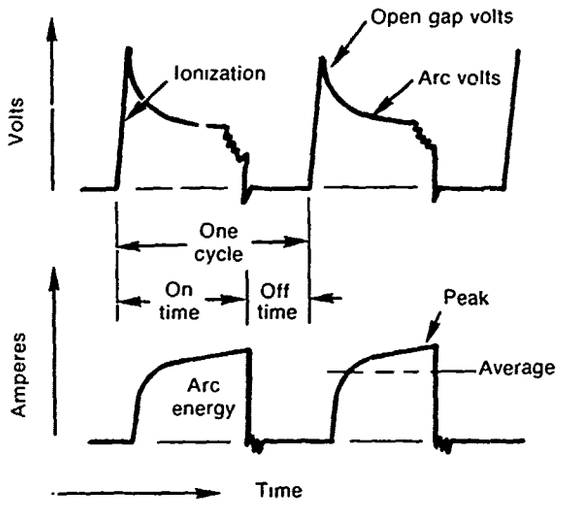


Figure 12.3–3 EDM parameter terminology. (Drawing at top courtesy of Agietron Corporation)

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TABLE 12.3–2 Steps to Select EDM Operating Parameters

ITEM	DATA
1. Type material, metallurgical state and melting point	Engineering drawing and material specifications.
2. Surface roughness required (finishing operation allowance—if any)	Engineering drawing. (Consider recast and heat-affected zone removal *only* if application function requires it and then *only* on the critically loaded areas or surfaces. Recommend removal of 2 times recast layer shown on micrograph of cross section of trial cut.)
3. Volume of material to be removed	From engineering drawing and raw stock shape, calculate in^3 [cm^3] to be removed.
4. Material removal rate—preliminary	Figures 12.3–4 to 12.3–6; tables 12.3–3 and 12.3–4.
5. Cutting time estimate	Material to be removed divided by material removal rate.
6. Select type electrode material	Tables 12.3–5, 12.3–6 and 12.3–12.
7. Make trade-offs among machining parameters	Table 12.3–7. According to work complexity, electrode, cost, desired precision, and quantity, a choice between high removal rate or normal or lowest wear must be fixed.
8. Select operating polarity and open circuit voltage	Table 12.3–8
9. Select specific parameters: On time—for roughing and finishing Current Capacitance Material removal rate Surface roughness End wear Corner wear	Figures 12.3–7 to 12.3–11 and table 12.3–9 are given for one specific electrode (graphite) and material (steel) combination. Similar curves on other material-electrode polarity combinations should be developed by the operator using his specific equipment, controls and materials. Many EDM builders have data for their own equipment, figures 12.3–12 to 12.3–15. For "drilling," see table 12.3–15 and figure 12.3–22.
10. Dielectric selection	Table 12.3–10; figures 12.3–16 and 12.3–17.
11. Flushing and filtration	Table 12.3–11. One of the most important parameters to secure high quality repeatability. Must be tailored to workpiece configuration, electrode shape and spark gap or overcuts. Consider use of orbiting electrodes, figure 12.3–2. Increasingly difficult flushing conditions, figure 12.3–18, can increase the machining cycle time. Filtration degree for recirculated dielectric should increase as the spark gap decreases and the flushing becomes more difficult. Recommend 75 μm (micron) filtration maximum.
12. Check availability of selected parameters on equipment to be used	Equipment ratings and control points. (Circuit type may require selection of capacitance.)
13. Cutting time—refined	Based on revised material removal rate from item 9 and material to be removed item 3, revised by excluding provision for flushing holes—if any. On finish cuts, it is a good approximation to assume unworn corners on electrodes when calculating material to be removed. Allow a multiplying factor for flushing difficulties, figure 12.3–18.
14. Overcut—the side wear between electrode and eroded workpiece—an allowance for electrode design	Figures 12.3–12 to 12.3–15. Increases with increase in spark intensity and material removal rate and voltage setting. Each workpiece material-electrode material combination has its own overcut, current, frequency charts.
15. Wear—an allowance for electrode design, stroke setting and accuracy of fine details	Figure 12.3–19; table 12.3–12. Corner wear is usually the most critical or limiting wear.
16. Number of electrodes	Use finishing electrode for fine details. It can frequently then serve as the roughing electrode on subsequent parts. Number to use depends on wear rate and depth of cut.
17. Voltage setting	Figure 12.3–20; table 12.3–8. For maximum efficiency, use minimum volts to achieve average current.
18. Select electrode manufacturing method	Often the most costly element for EDM. Many fabrication/machining methods available. Choice depends on electrode material production rate, shape and costs, tables 12.3–13 and 12.3–14.
19. Electrode design	See items 2, 14, 15, 16 and 18.
20. Assess extent of altered material zones on surface: recast, heat-affected zone (HAZ)	Figure 12.3–21. Depth of HAZ below recast approximately equal to depth of recast. (Note: If EDM'd surface is highly stressed, subject to stress corrosion or otherwise critically loaded, steps should be taken to ameliorate these surface integrity effects.)
21. Trial cut	Several test cuts are recommended in the workpiece material using the selected conditions to check the resulting values for overcut, removal rate, surface roughness and wear ratio. These data will, in time, provide the operator with his own machinability tables for his particular conditions.

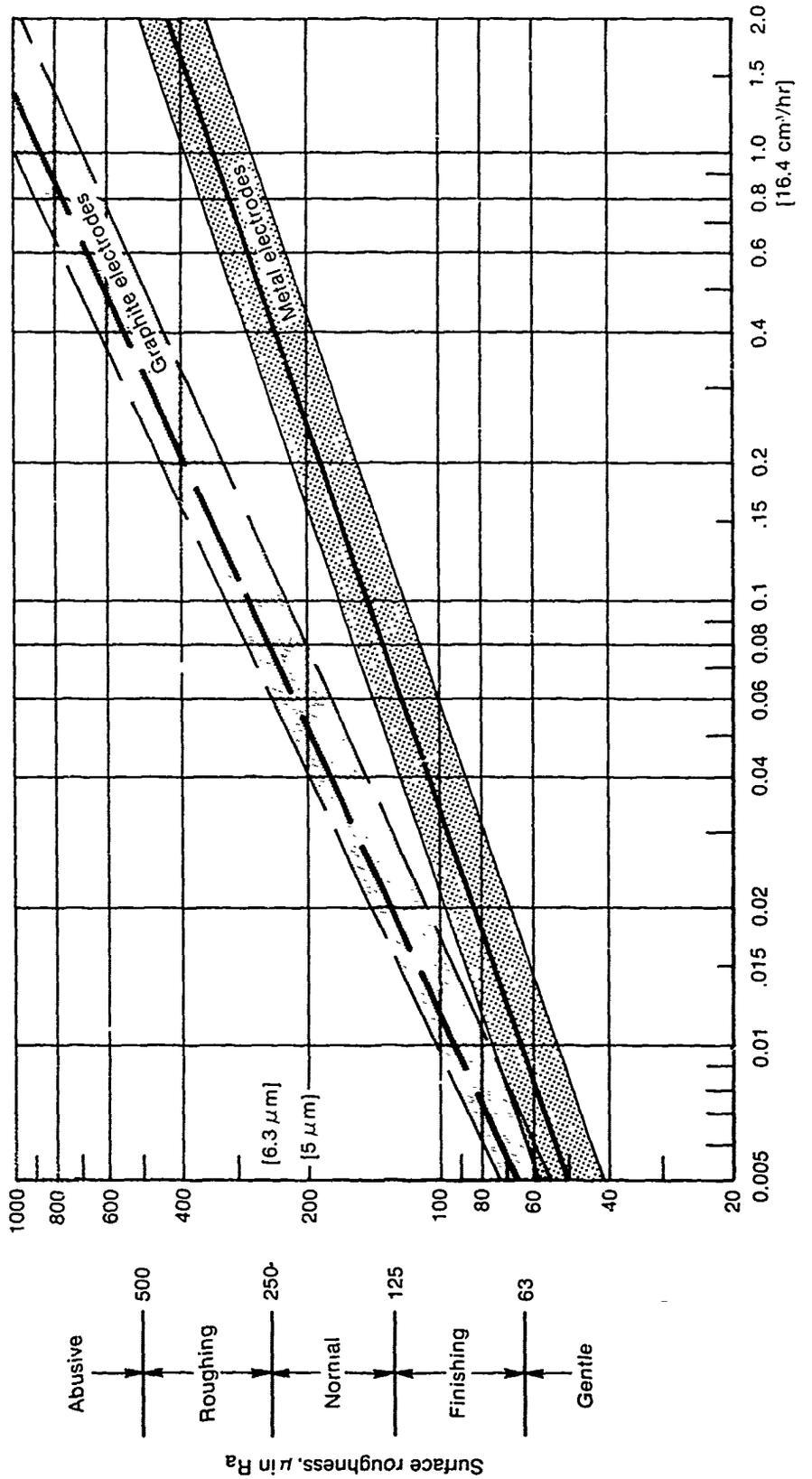


Figure 12.3-4 Material removal rate versus surface roughness for EDM with graphite or metal electrodes. (Modified from G. Bellows, Surface integrity from electrical discharge machining of superalloys, Report R72AEG236, General Electric Company, 1972, p. 18)

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TABLE 12.3–3 Relationship of Metal Removal Rate in EDM to Surface Roughness and Expected Recast Material

PROCESSING LEVEL	SURFACE ROUGHNESS, R_a		METAL REMOVAL RATE		EXPECTED RECAST MATERIAL			
					Predominant		Maximum	
	μin	μm	in³/hr	cm³/hr	in	mm	in	mm
Gentle	<63	<1.6	<0.003	<0.05	<0.00022	<0.0056	0.00054-0.00060	0.014-0.015
Finishing	63-125	1.6-3.2	0.003-0.018	0.05-0.30	0.00022-0.00028	0.0056-0.0071	0.001-0.0013	0.025-0.033
Normal	125-250	3.2-6.3	0.018-0.42	0.30-6.9	0.00028-0.00043	0.0071-0.011	0.0022-0.0033	0.056-0.084
Roughing	250-500	6.3-12.5	0.42-1.5	6.9-24.6	0.00043-0.00068	0.011-0.017	0.0055-0.0090	0.14-0.23
Abusive	>500	>12.5	>1.5	>24.6	>0.00068	>0.017	to 0.014	to 0.36

TABLE 12.3–4 EDM Metal Removal Rates

CURRENT	METAL REMOVAL RATE*			
	Graphite Electrode		Metal Electrode	
A	in³/hr	cm³/hr	in³/hr	cm³/hr
25	1.5	24.6	0.75	12.3
50	3.0	49.2	1.5-1.8	24.6-29.5
100	5.5	90.1	2.7-4.4	44.2-72.1
200	9.0	147.5	†	†
400	16.0	262.2	†	†

NOTE: A common *rough* estimating guide is 1.0 in³/hr [16.4 cm³/hr] for 20 amperes

*Based on steel workpiece.

† Graphite is normally used for high-ampere applications.

TABLE 12.3–5 Some Physical Properties of EDM Electrode Materials

ELECTRODE MATERIAL	MELTING POINT	BOILING POINT	HEAT TO VAPORIZE 1 cm³ FROM ROOM TEMPERATURE	THERMAL CONDUCTIVITY Ag=100	ELECTRICAL CONDUCTIVITY Ag=100	THERMAL EXPANSION per °C	STRENGTH	MODULUS OF ELASTICITY
	°C	°C	cal/cm³	percentage	percentage	* x 10⁻⁶	psi	psi x 10⁶
Copper	1,083	2,580	12,740	94.3	96.5	16.0	35,000	18.0
Graphite	*	Over 4,000	Approx. 20,000	30.0	0.1	4.5	5,000	0.86
Tungsten	3,395	5,930	22,680	29.6	48.1	4.6	600,000	51.0
Iron	1,535	2,800	16,900	16.2	16.2	15.0	40,000	27.0

SOURCE: E. I. Shobert, II, What happens in EDM, *Manufacturing Engineering* 77 (July 1976), p. 39.

*Sublimes or boils before melting at atmospheric pressure.

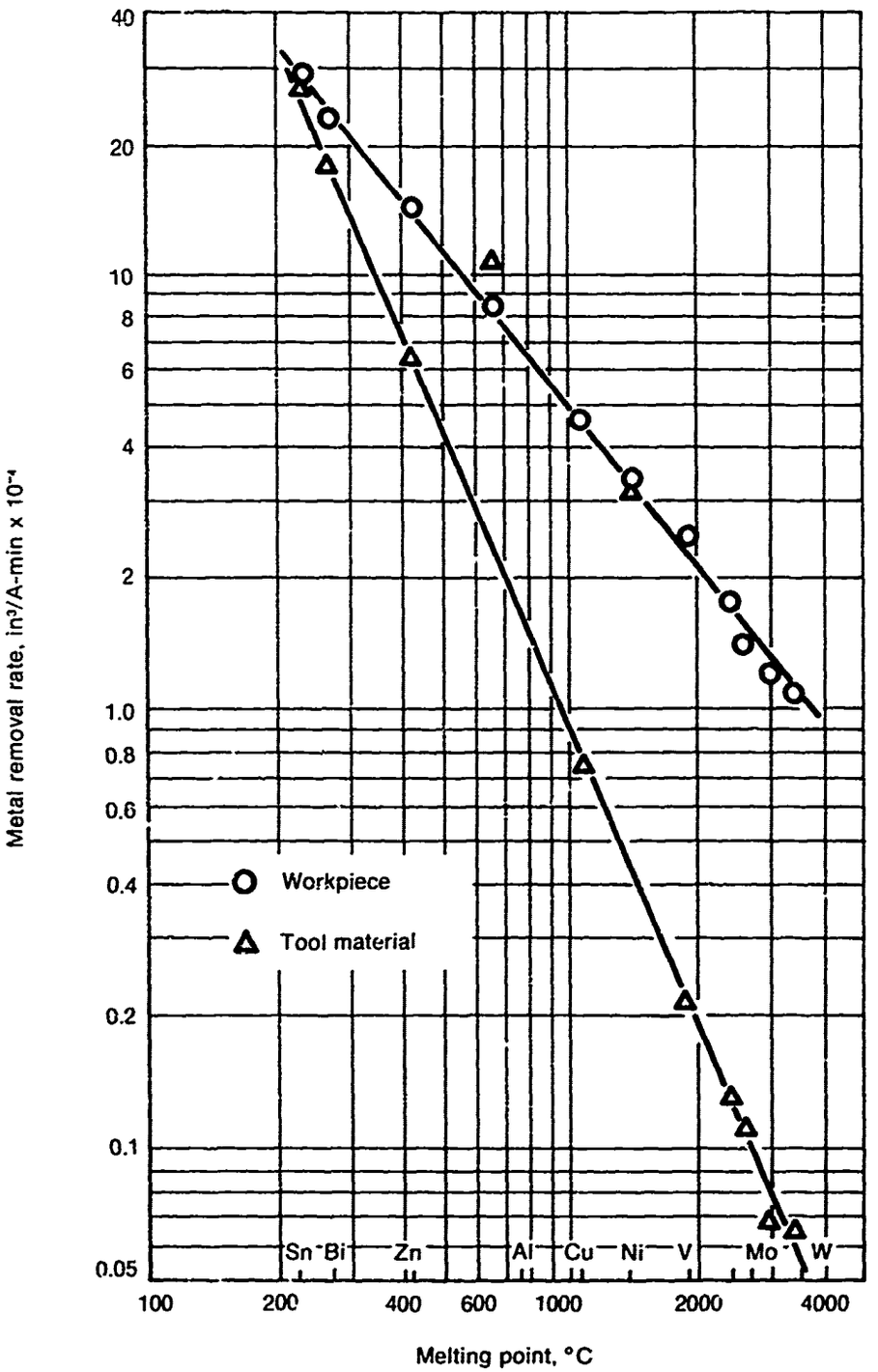


Figure 12.3–5 Average metal removal rate versus melting point. (L. J. Quackenbush and W. N. Lawrence, *Electrical discharge machining for the 70's*, Ann Arbor, MI: University of Michigan, 1971, p. 19)

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TABLE 12.3–6 Selection of EDM Electrode Material

ELECTRODE MATERIAL	GUIDE-LINES See Footnote	FORM	CORNER WEAR RATIO IN FINISHING	END WEAR RATIO IN ROUGHING	RELATIVE COST	MACHIN-ABILITY RATING	RECOM-MENDED USES	USES NOT RECOM-MENDED
Graphite	1	blocks, rod, tube, bar	5:1	to 100:1	low	excellent	tooling	
Copper	2	bar, rod, sheet, wire, tube, forgings, stampings	1:1	2:1	medium	good	holes, slots	high accuracy and detail
Copper-graphite	3	blocks, rods	2:1	4:1	medium	fine	general purpose	
Brass	4	same as copper	0.7:1	1:1	low	good	holes and cavity sinking	high accuracy
Zinc alloys	5	cast, die casting	0.7:1	2:1	low	good	forging die cavities	holes
Steel	6	all forms	1:1	2:1	low	excellent	through holes	carbides
Copper-tungsten	7	bar, flats, shim stock, rod, wire, tube	3:1	8:1	medium	fair	slots, carbides	large areas
Silver-tungsten	8	sintered	8:1	12:1	high	fair	small slots, holes and intricate details	large areas
Tungsten	9	wire, rod, ribbon	5:1	10:1	high	poor	small holes	irregular holes

NOTES:

1. GRAPHITE permits fast EDM rates and best wear ratio, is easy to machine, and offers excellent stability. Surface roughness produced on the workpiece is related to graphite particle size and density. Rotating graphite electrodes can produce roughness values less than 40 microinches R_a [1.0 μm]. A number of different grades are available. Easily attached to tool holder with conductive cement. Needs good dielectric flow conditions.
2. COPPER produces fine finishes and is excellent for No-wear EDM. Easily machined or coined. Low wear ratio.
3. COPPER-GRAPHITE has best characteristics of both materials—more conductivity and strength than graphite. Will work well under poor flushing.
4. BRASS has a higher wear ratio than copper but can be economically machined for many operations. Not recommended for EDM of tungsten carbide.
5. ZINC-TIN ALLOYS are used for high production where many identical electrodes are needed because they are easily cast in metal molds. Can be pressure-cast and coined to an existing cavity. Complex shapes reproduced more readily than machining. Reusable by remelting. Not recommended for fine detail. Usually has poor wear ratio.
6. STEEL gives slow stock removal rates. Applicable when doing parting-line matching. Greater heat-affected zones. Readily machined, but wear ratio unsatisfactory for some types of steel.
7. COPPER-TUNGSTEN has good wear and finish characteristics. Can be brazed and has good rigidity. Used for close tolerances, fine detail, and low wear. Used on carbide. Used in slotting operations. Metal removal rates are lower than graphite, and the cost is higher. Use positive polarity on electrode when machining steels. Molded Cu-W electrodes are available for complex shapes or repetitive production.
8. SILVER-TUNGSTEN resists corner wear. Good for accurate detail or thinecuts. Provides low wear and faster removal rates than copper-tungsten. Is more expensive and generally limited to machining intricate carbide dies.
9. TUNGSTEN has high rigidity which makes it excellent for EDM of holes under 0.010-inch [0.25 mm] diameter. High cost but good wear ratio.

TABLE 12.3–7 Trade-off Conditions Among EDM Parameters

SITUATION A	SITUATION B
High material removal rates	Low material removal rates
High surface roughness	Low surface roughness
Low frequency (long cycle time	High frequency (short cycle time)
High arc energy (high amperes and long on-time)	Low arc energy (low amperes and short on-time)
Large arc gap	Small arc gap
High overcut	Low overcut
Modest electrode wear	Low electrode wear

TABLE 12.3–8 EDM Polarity and Open Circuit Voltage Guidelines

ITEM	ELECTRODE (TOOL) POLARITY*	
	Negative	Positive
Metal removal rate	Medium to high	Medium to low
Work-to-wear ratios	Medium	High to "no wear"†
Surface roughness		
steels	Good to rough	Good to excellent
other materials	Good (depends on other parameters)	Good (depends on other parameters)

WORKPIECE MATERIAL	ELECTRODE MATERIAL	ELECTRODE POLARITY*	OPEN CIRCUIT VOLTAGE V
Steel	Steel	Positive	Up to 270
Steel	WCu	Positive	Up to 100
Steel	Graphite	Positive	Up to 100
Steel	Cu	Positive	Up to 150
Steel	Cu	Negative	Up to 270
Copper	WCu	Positive	Up to 100
Copper	Cu	Negative	Up to 100
Carbides	WCu	Negative	Up to 270

NOTE: These guidelines are subject to change depending upon power pack characteristics and voltage needed to attain desired average currents and cutting rates.

*Normal or "standard" polarity is usually considered to be positive on the workpiece and negative on the electrode tool However, since the advent of solid state controls (circa 1970), some writings have reversed this, particularly for some materials where better wear ratios have been experienced

†"No wear" EDM is the special combination of operating parameters that on some workpiece material-electrode material combinations yield wear ratios 100:1 or better, see table 12.3–12.

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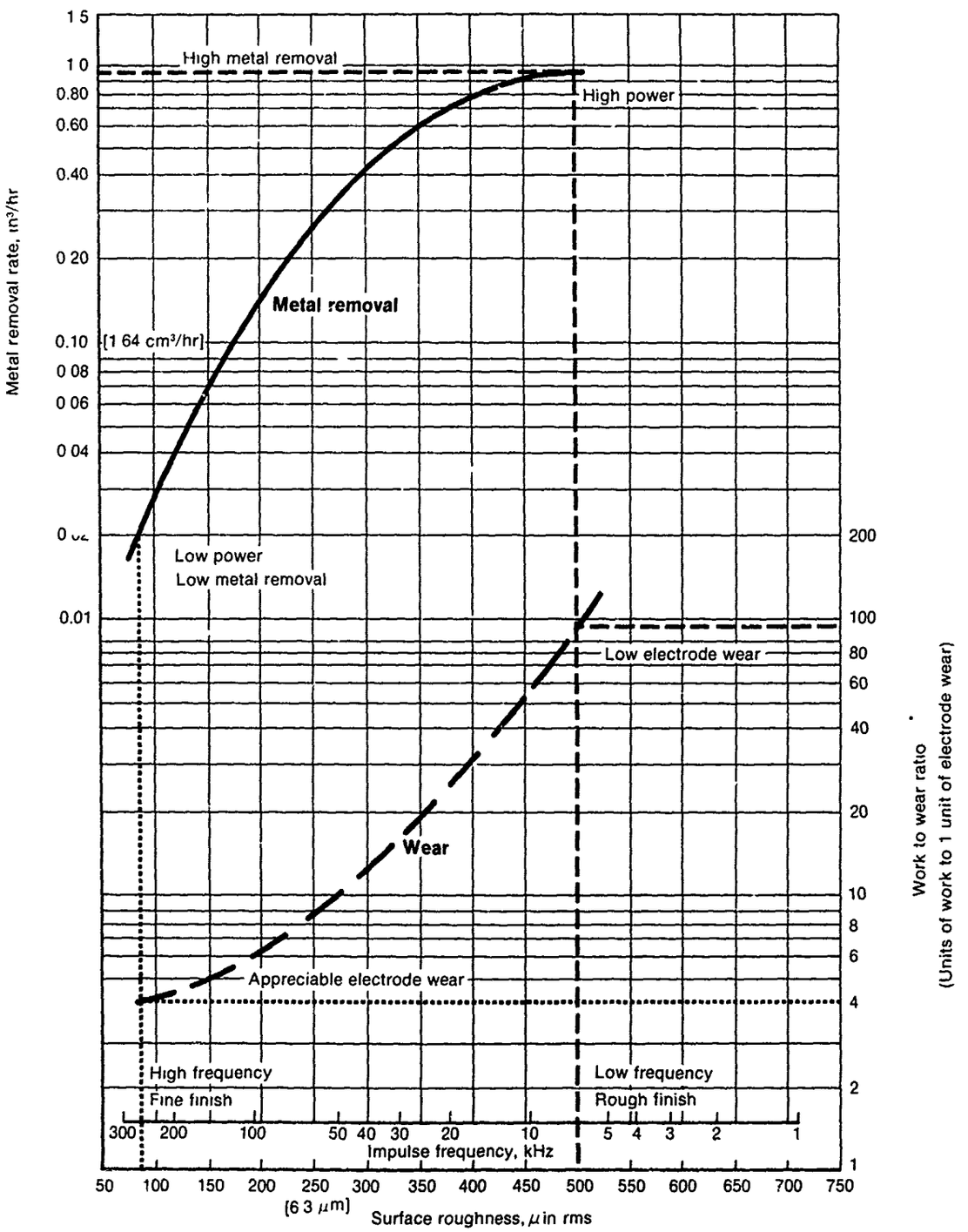


Figure 12.3–6 Interrelations of EDM process variables. (Courtesy of Poco Graphite, Inc.)

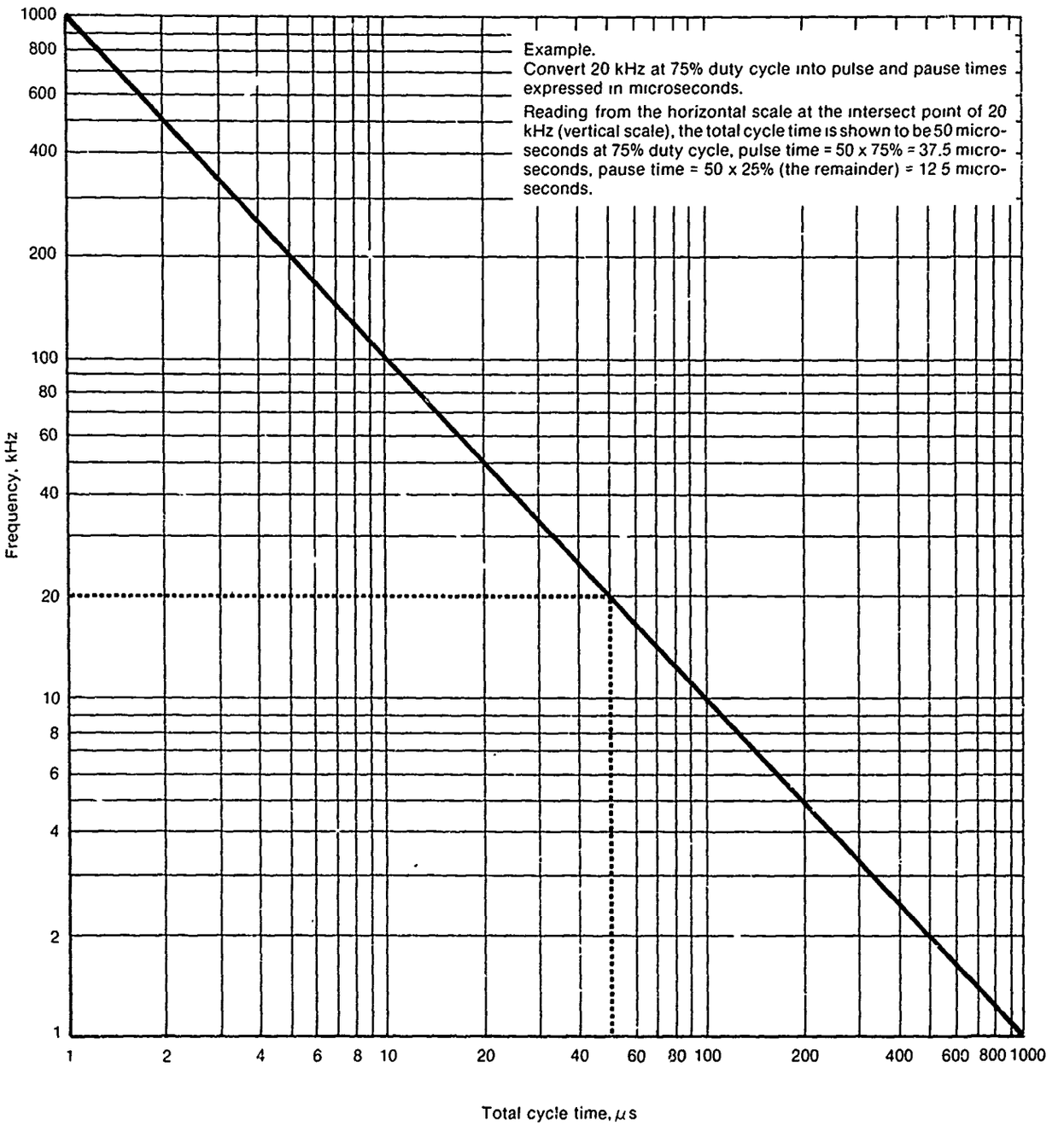


Figure 12.3–7 Cycle time—frequency conversion. (Courtesy of Poco Graphite, Inc.)

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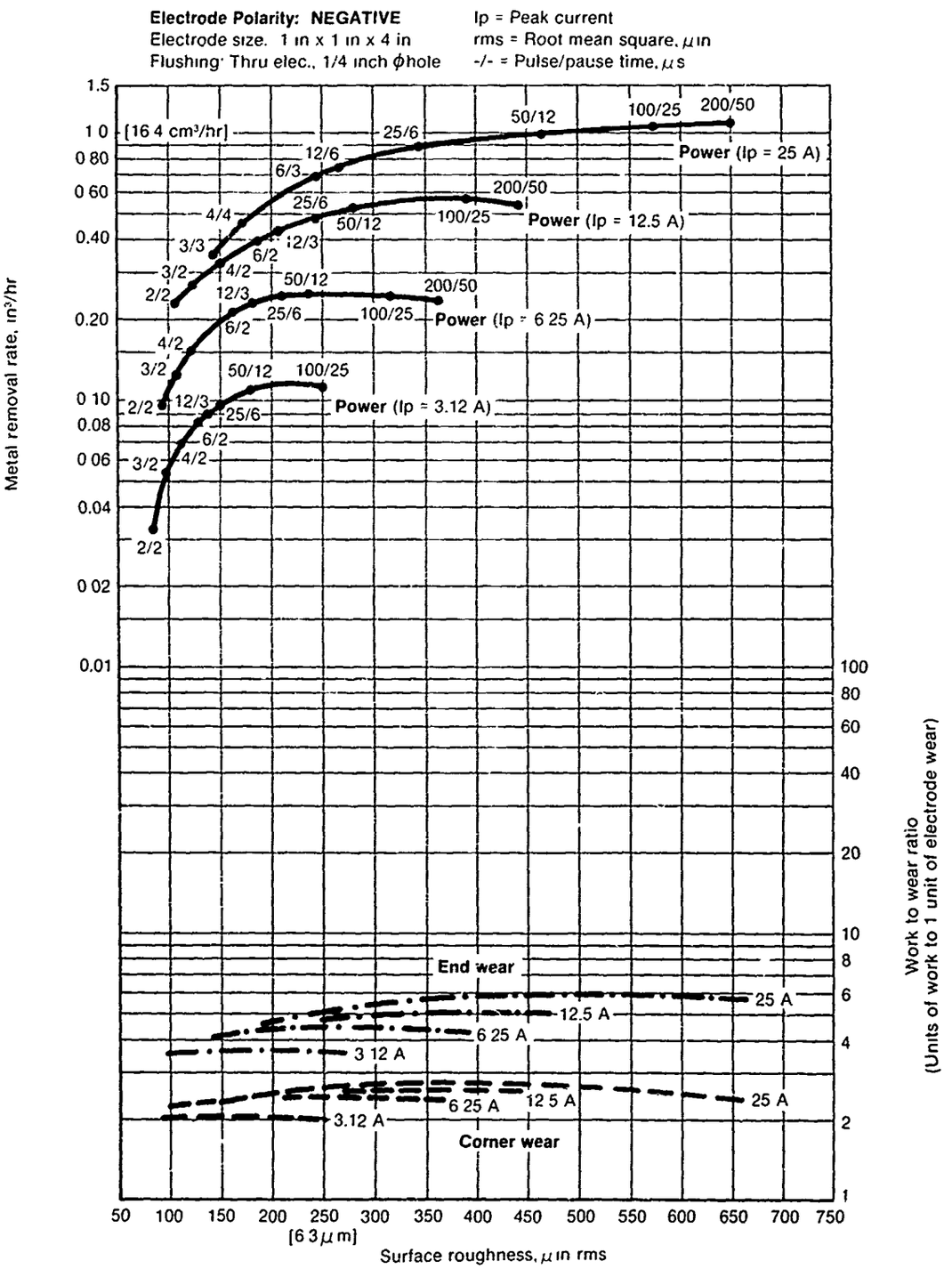


Figure 12.3–8 Data for Poco EDM-1 electrode (negative polarity) cutting tool steel. (Courtesy of Poco Graphite, Inc.)

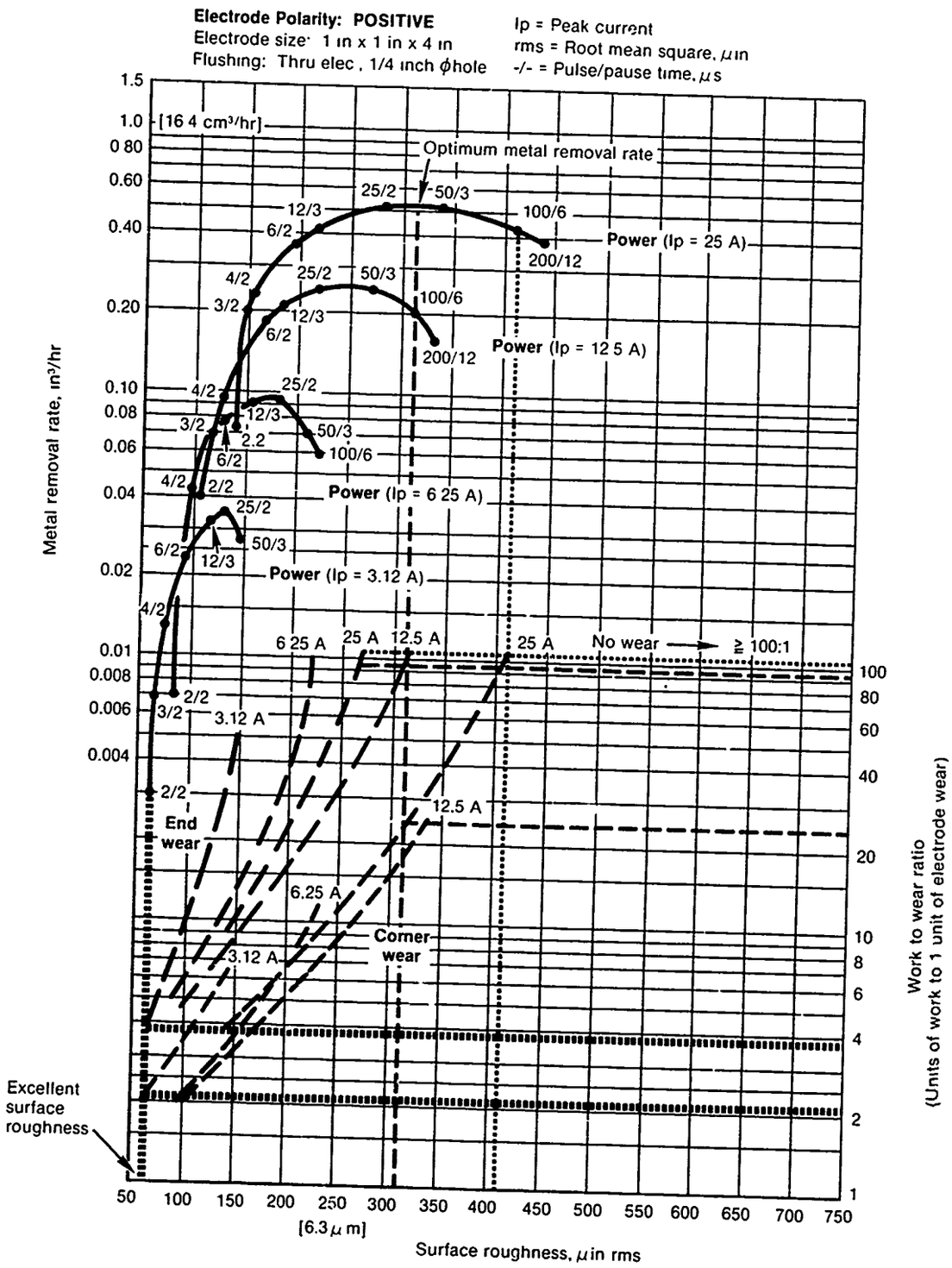


Figure 12.3–9 Data for Poco EDM-3 electrode (positive polarity) cutting tool steel. (Courtesy of Poco Graphite, Inc.)

12.3 Electrical Discharge Machining—EDM

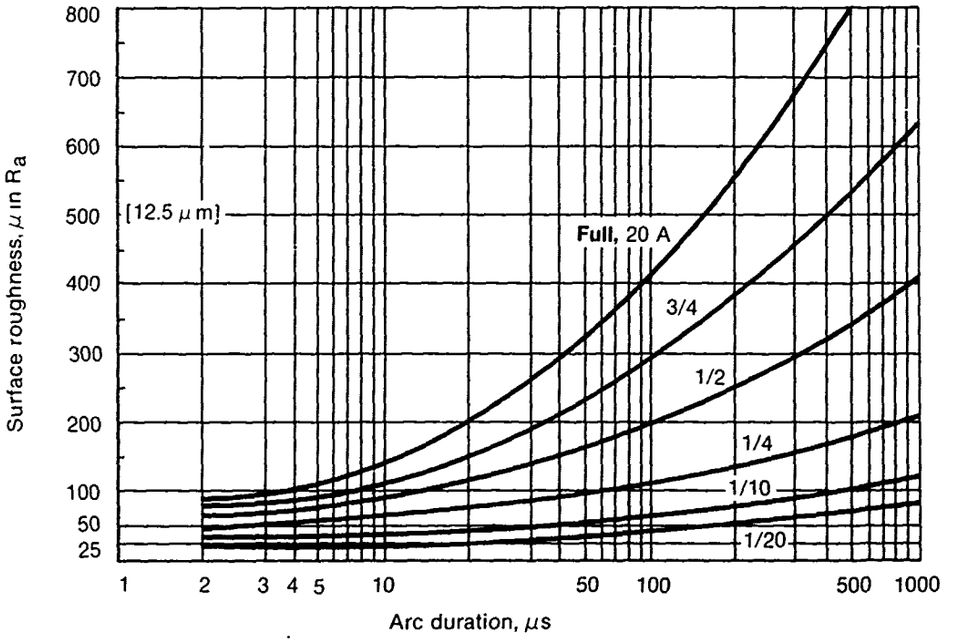


Figure 12.3–10 Surface roughness versus arc duration at various currents for EDM of steel with graphite electrodes. (Courtesy of Hansvedt Engineering, Inc.)

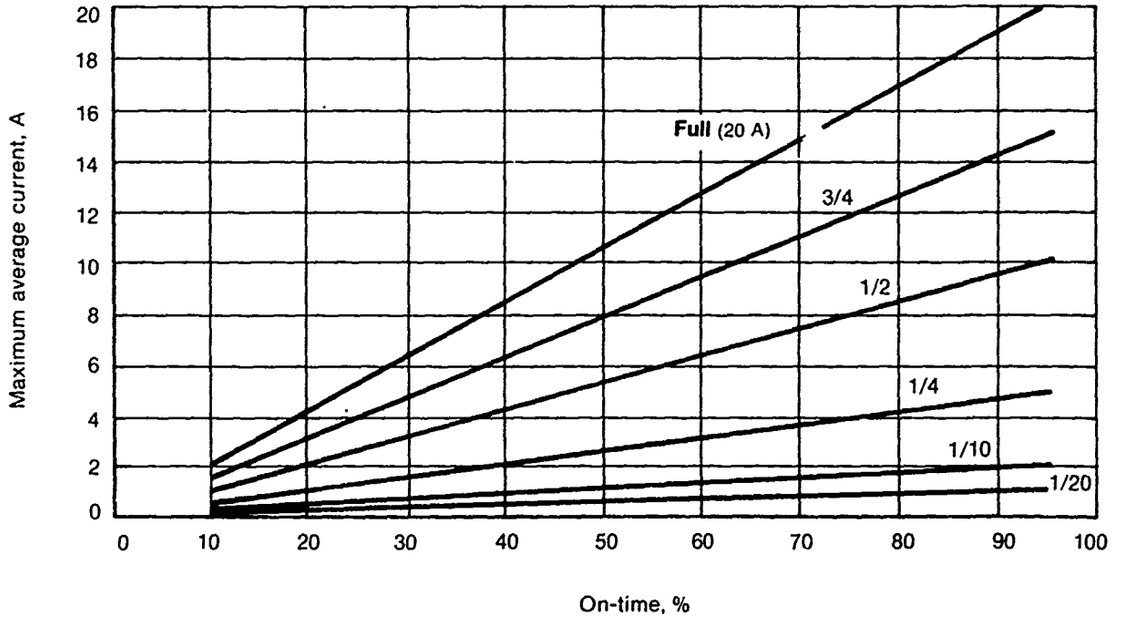
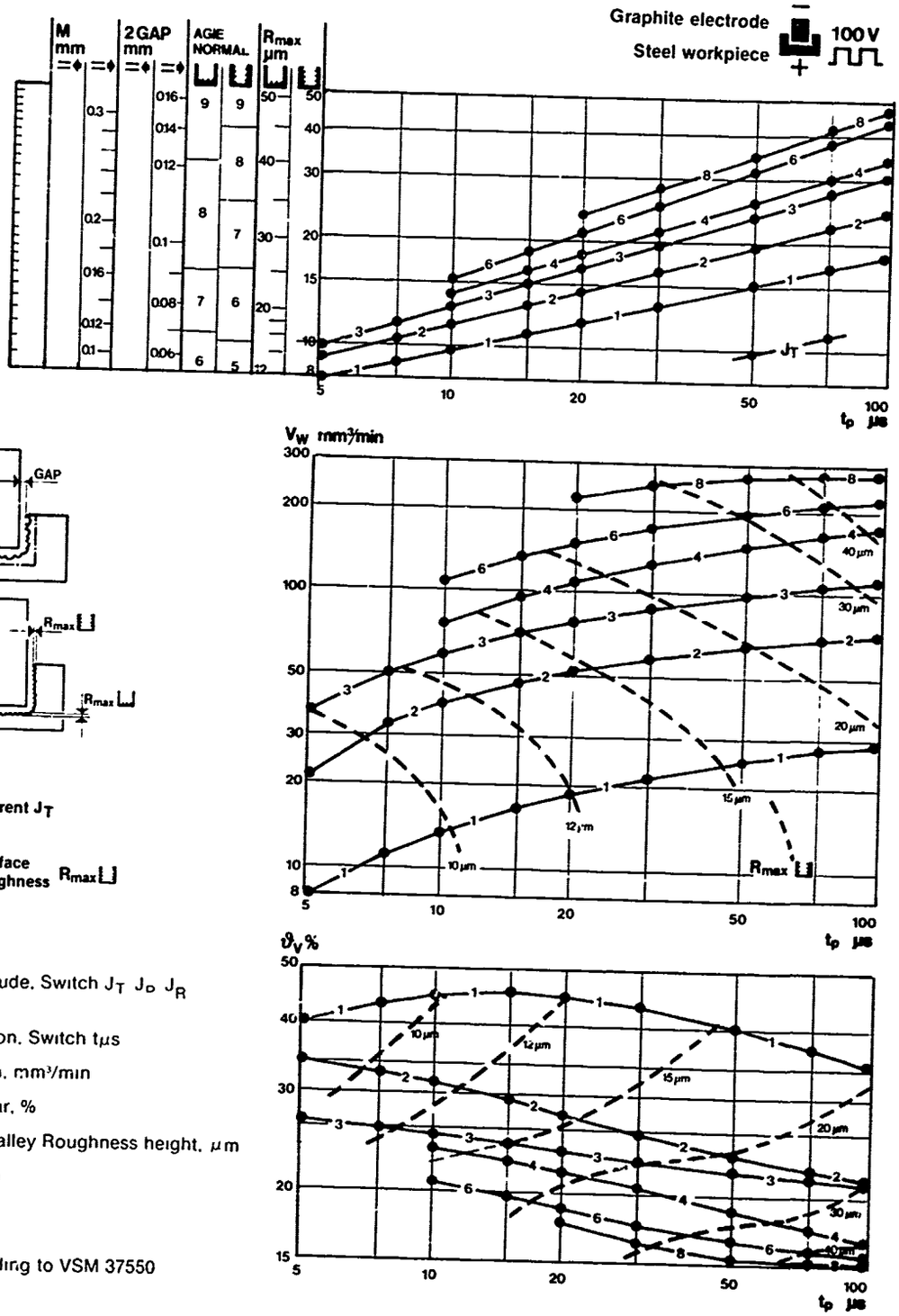


Figure 12.3–11 Maximum average current versus percent age of on-time for EDM of steel with graphite electrodes. (Courtesy of Hansvedt Engineering, Inc.)



J_T Current amplitude. Switch J_T J_D J_R
$1J_T = 3A$

tp (μs) Impulse duration. Switch tμs

V_W Rate of erosion. mm³/min

ϑ_V Volumetric wear, %

R_{max} Max Peak-to-Valley Roughness height, μm

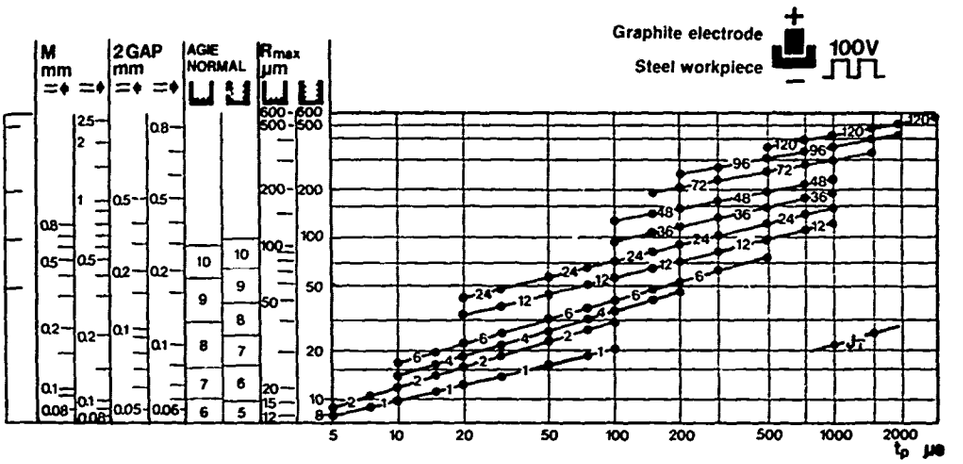
GAP Spark gap, mm

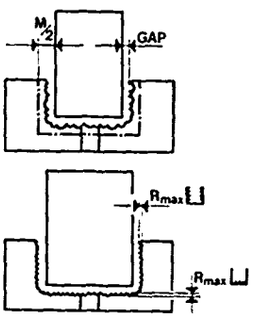
M Undersize, mm

Test conditions according to VSM 37550

Figure 12.3–12 Parameter selection for EDM. (Courtesy of Agietron Corporation)

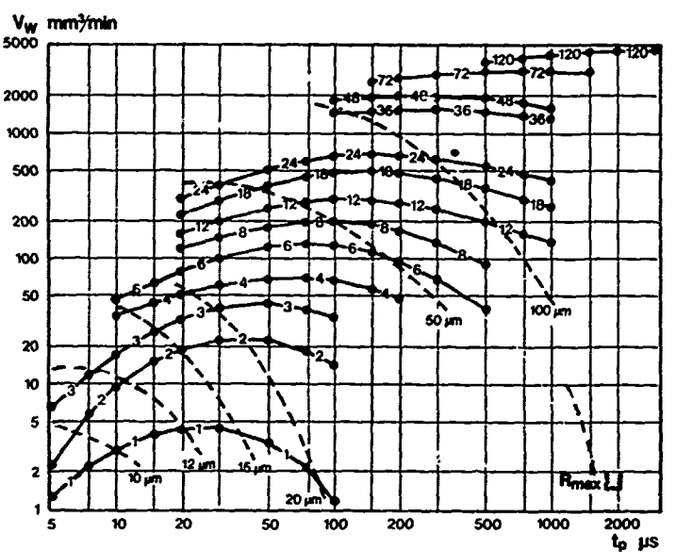
12.3 Electrical Discharge Machining—EDM

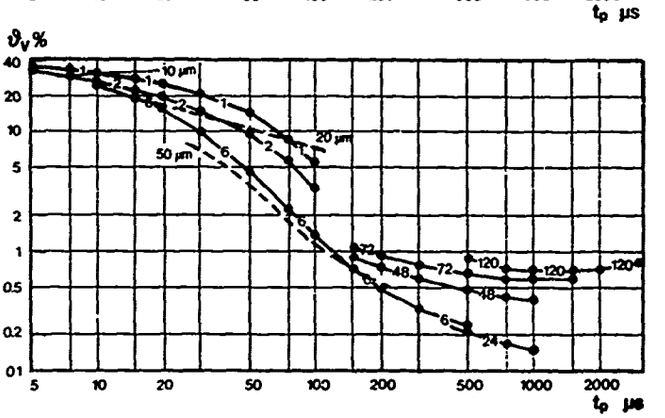




Current J_T

Surface roughness R_{max}





J_T Current amplitude. Switch J_T. J_P. J_R: $1J_T = 3A$

tp(μs) Impulse duration. Switch tμs

V_W Rate of erosion. mm³/min

ϑ_v Volumetric wear. %

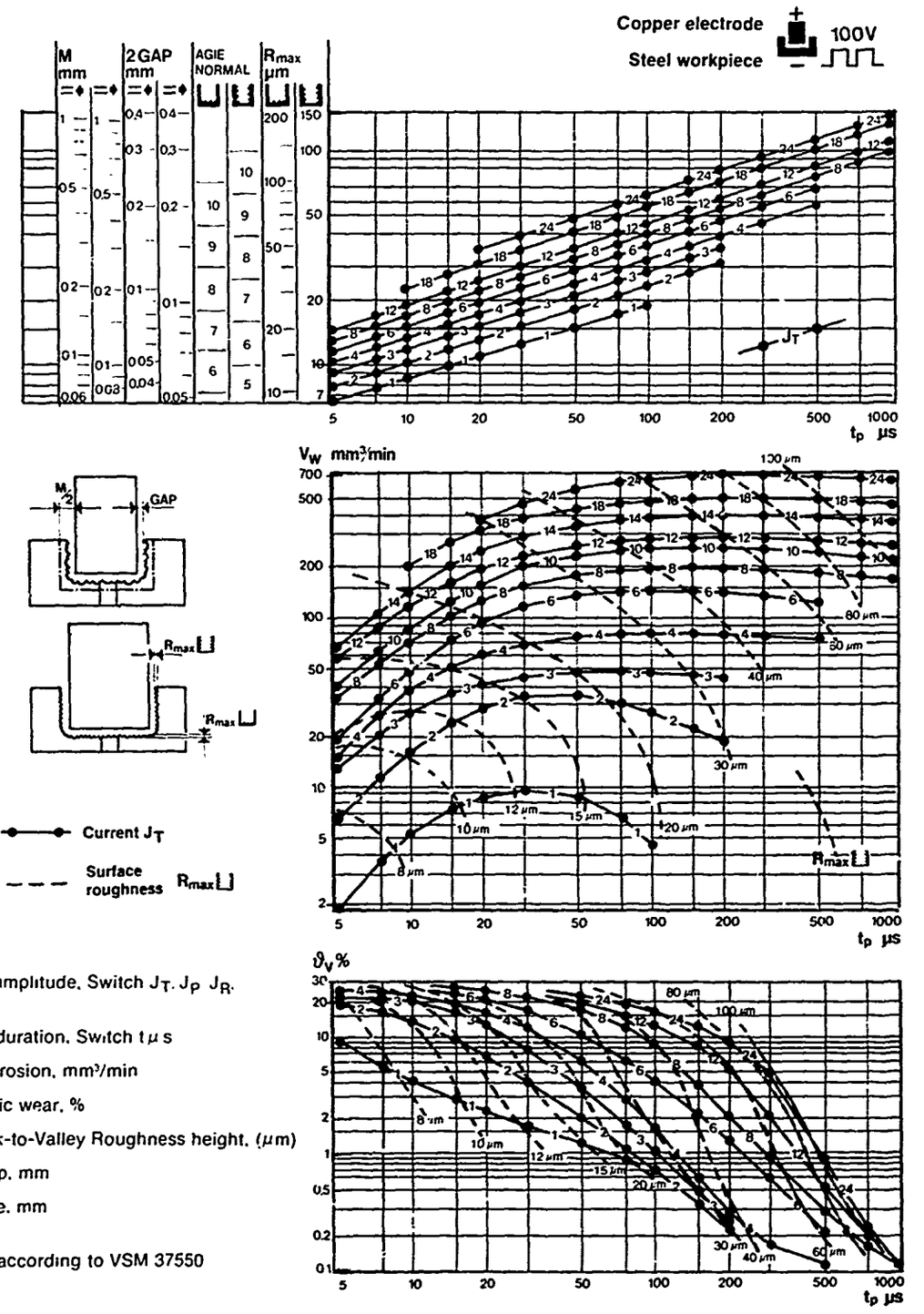
R_{max} Max Peak-to-Valley Roughness height .μm

GAP Spark gap. mm

M Undersize. mm

Test conditions according to VSM 37550

Figure 12.3–13 Parameter selection for EDM. (Courtesy of Agietron Corporation)



J_T Current amplitude. Switch J_T. J_P J_R. $1J_T = 3A$

$t_p(\mu s)$ Impulse duration. Switch $t\,\mu s$

V_w Rate of erosion. mm^3/min

ϑ_v Volumetric wear. %

R_{max} Max Peak-to-Valley Roughness height. (μm)

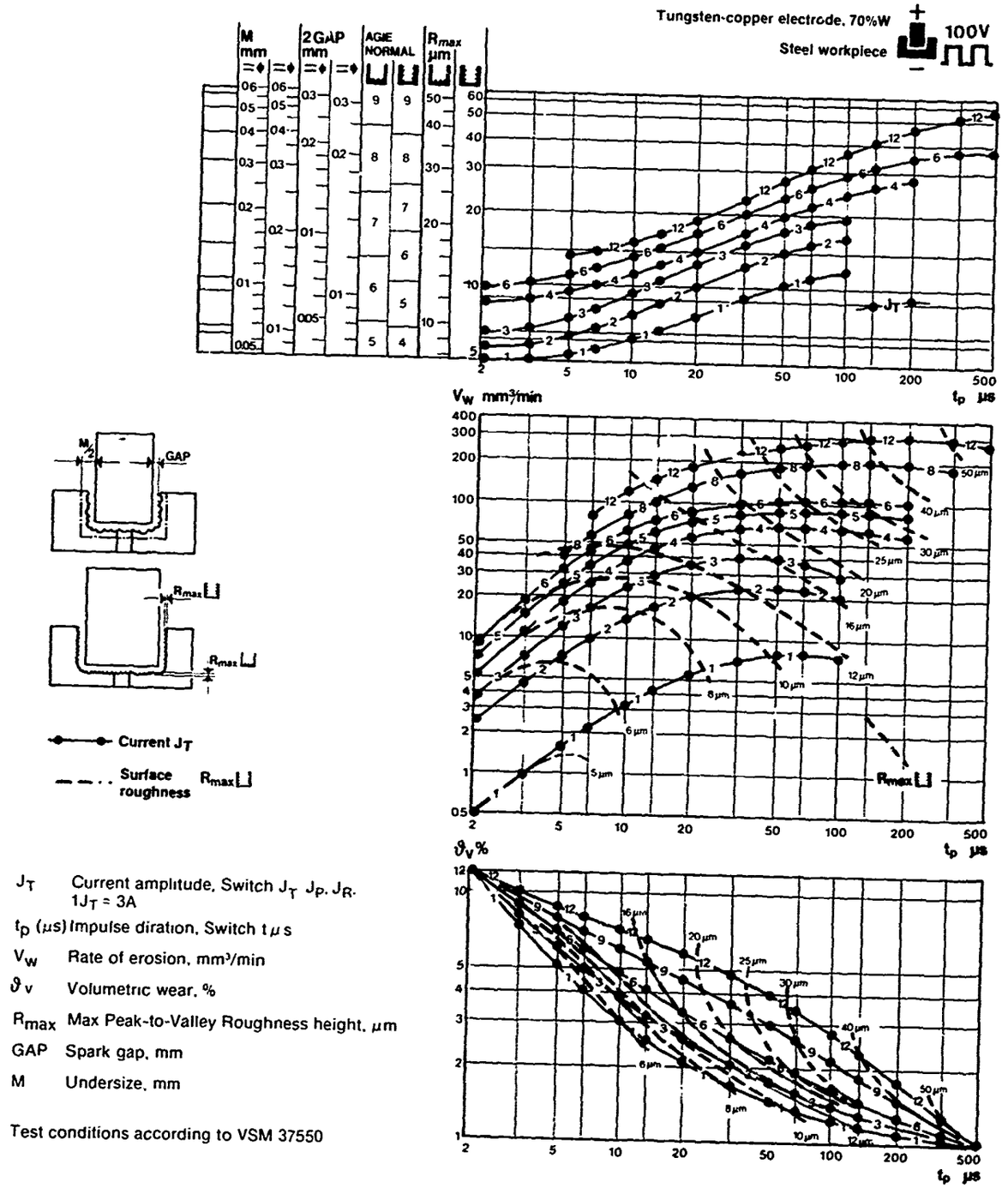
GAP Spark gap. mm

M Undersize. mm

Test conditions according to VSM 37550

Figure 12.3–14 Parameter selection for EDM. (Courtesy of Agietron Corporation)

12.3 Eiectrical Discharge Machining—EDM



J_T Current amplitude, Switch J_T J_P, J_R. $1J_T = 3A$

t_p (μs) Impulse diration, Switch t μ s

V_w Rate of erosion, mm³/min

ϑ_v Volumetric wear, %

R_{max} Max Peak-to-Valley Roughness height, μm

GAP Spark gap, mm

M Undersize, mm

Test conditions according to VSM 37550

Figure 12.3–15 Parameter selection for EDM. (Courtesy of Agietron Corporation)

TABLE 12.3–9 Pulse/Pause Times versus Duty-Cycles: Conversion Chart

PULSE TIME μS	PAUSE TIME μS			
2	2			
3	3	2		
4	4	2		
6	6	3	2	
12	12	6	3	
25	25	12	6	2
50	50	25	12	3
100	100	50	25	6
200	200	100	50	12
400	400	200	100	25
800	800	400	200	50
1,600	1,600	800	400	100
	APPROXIMATE DUTY CYCLE			
	50%	66%	80%	95%

SOURCE: Poco Graphite, Inc., Decatur, TX.

TABLE 12.3–10 EDM Dielectrics

Principal functions of the dielectric in EDM

- **Insulate** until required conditions are achieved.
- **Flush** particles out of spark gap.
- **Cool** machined particles, tool and workpiece.

Desired properties of the dielectric

- Low viscosity.
- High dielectric strength.
- High flash point.
- Freedom from acid, alkali and corrosion products (particularly sulfur compounds when machining sulfur-free steels).
- Low toxicity (particularly chlorine compounds).

Dielectrics used in EDM

- Hydrocarbon oils—the most widely used dielectric. Select type and viscosity to suit type cut, gap size and surface roughness (see figure 12.3–16). Generally cuts more smoothly after a few minutes use, or conditioning.
- Water—distilled and deionized. Used principally for micromachining and wire cutting machines (EDWC).
- Kerosene—good for superfinishing, but infrequently used. Deodorizing recommended and attention to safety precautions. Useful with tungsten electrodes.
- Silicone oils—infrequently used; more costly.
- Ethylene glycol solutions—rarely used.
- Gas—very specialized applications.

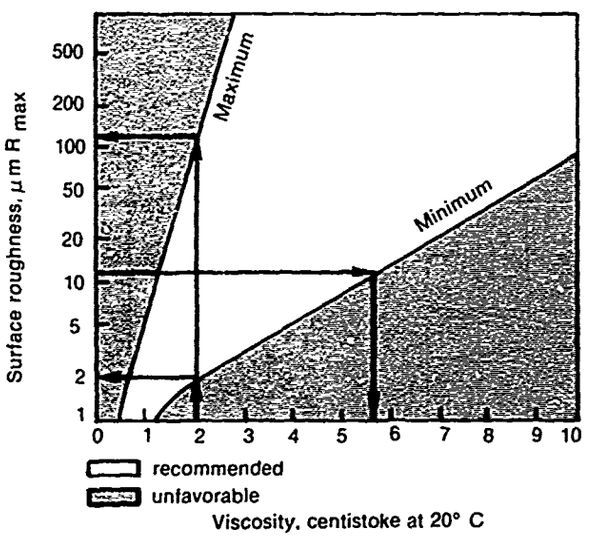


Figure 12.3–16 Recommended dielectric viscosity for EDM as a functior of peak to valley, R_{max} surface roughness. (Courtesy of Agietron Corporation)

12.3 Electrical Discharge Machining—EDM

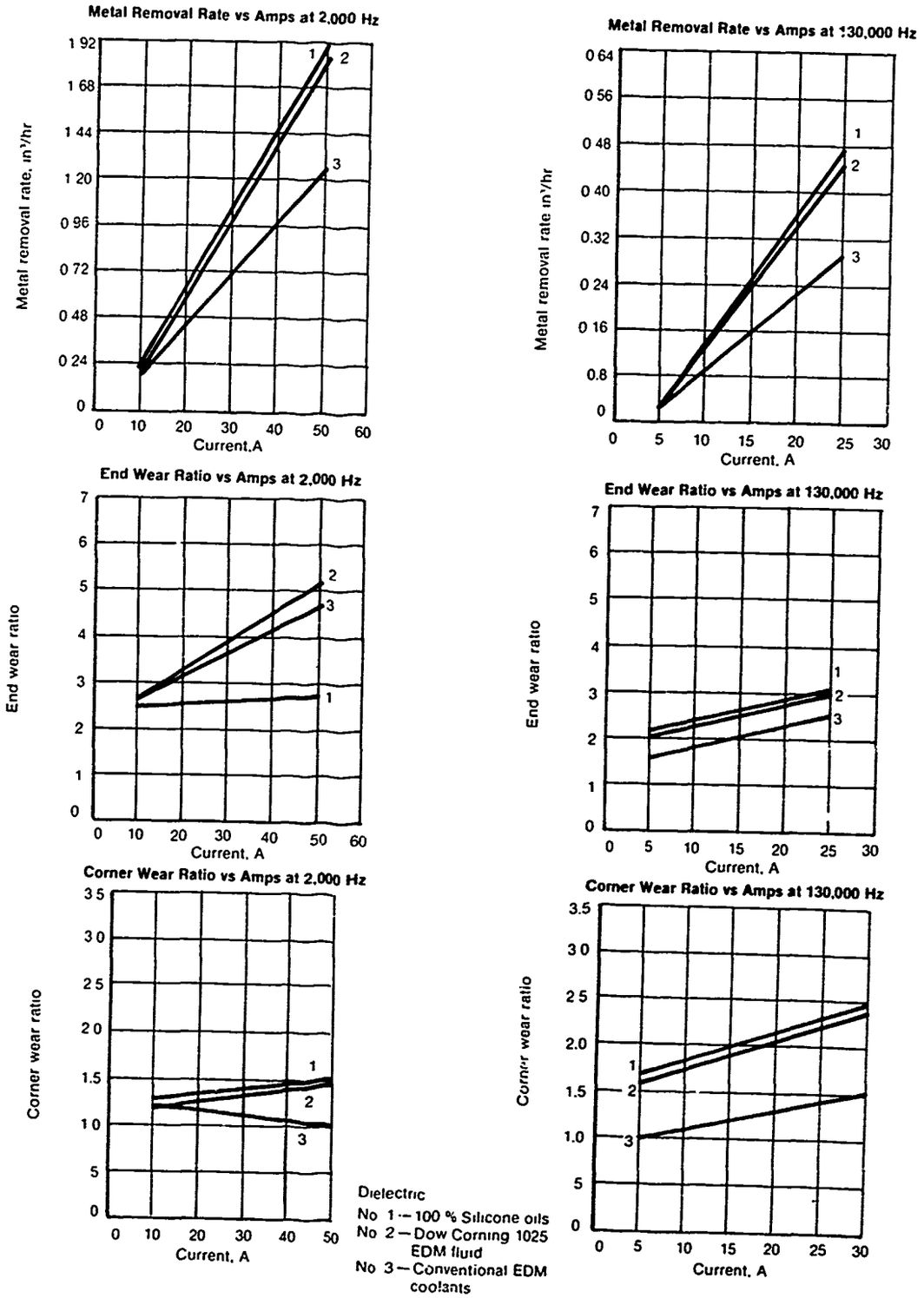


Figure 12.3–17 Effect of dielectric on operating parameters. (Courtesy of Dow Corning Co.)

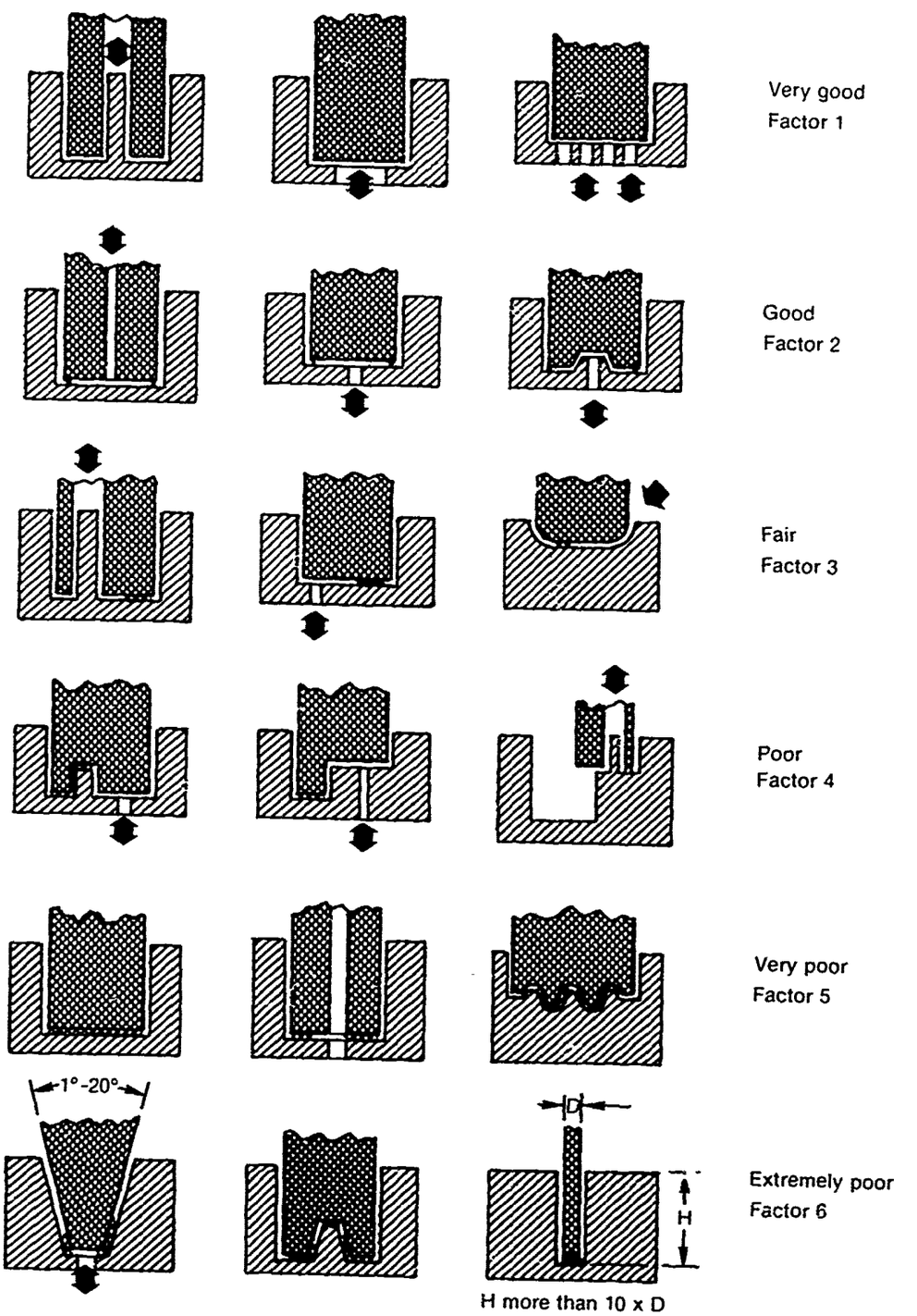


Figure 12.3–18 Flushing evaluation chart. (L. Houman, How to estimate EDM time requirements, *Metal Stamping*, 11 (June 1977), p. 15)

12.3 Electrical Discharge Machining—EDM

TABLE 12.3–11 Flushing Techniques Used in EDM

- Flow over workpiece cutting area*
- Submerge work in tank
- Pressure through electrode or workpiece
- Suction through electrode or workpiece—or both pressure and suction
- Ram cycling
- Vibration on workpiece
- Invert cavity (workpiece on ram)

*Careful fire safety check recommended.

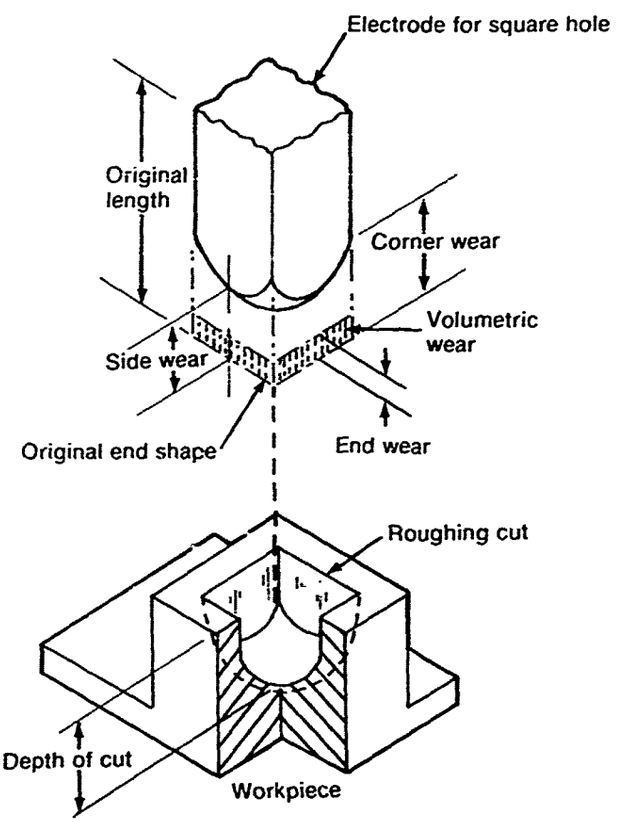


Figure 12.3–19 Types of electrode wear in EDM. (Modified from H. W. Yankee, *Manufacturing processes*, Englewood Cliffs, NJ: Prentice-Hall, 1979, p. 311)

TABLE 12.3–12 Electrode Wear Ratio Chart

PART 1

ELECTRODE MATERIAL	WORKPIECE MATERIAL	POLARITY ON ELECTRODE	WEAR RATIO* percentage
Aluminum	Steel	Positive	700
Brass	Brass	Negative	50
Brass	Carbide	Negative	700
Brass	Steel	Negative	200
Brass	Tungsten	Negative	700
Carbide	Carbide	Negative	150
Copper	Steel	Negative	200
Copper-tungsten	Carbide	Negative	150
Copper-tungsten	Copper-tungsten	Negative	50
Copper-tungsten	Steel	Positive	30
Copper-tungsten	Tungsten	Negative	75
Zinc-tin	Steel	Negative	500
Graphite	Steel	Negative	50
Graphite	Carbide	—	150 (with caution)
Silver-tungsten	Steel	Negative	20
Steel	Steel	Positive	150
Graphite	Steel	Positive†	<1
Copper	Steel	Positive†	<1

PART 2

ELECTRODE MATERIAL	WORKPIECE MATERIAL	POLARITY ON ELECTRODE	ELECTRODE CORNER WEAR‡ percentage
Graphite	Steel	Positive	<1
Graphite	Steel	Negative	30
Graphite	Inconel alloy 718	Positive	<1
Graphite	Inconel alloy 718	Negative	35
Graphite	Aluminum	Positive	<1
Graphite	Aluminum	Negative	15
Graphite	Copper	Negative	40
Copper-graphite	Carbide	Negative	62
Copper	Carbide	Negative	50
Copper	Steel	Positive	<1
Copper	Copper	Negative	40
Copper	Graphite	Negative	40
Copper	Aluminum	Positive	<1
Copper-tungsten	Steel	Positive	6
Copper-tungsten	Graphite	Negative	40
Copper-tungsten	Copper	Negative	36
Copper-tungsten	Copper-tungsten	Negative	80
Copper-tungsten	Graphite	Positive	70
Copper-tungsten	Carbide	Negative	40
Brass	Steel	Negative	100
Brass	Carbide	Negative	500
Steel	Steel	Positive or Negative	100

SOURCE: Part 1, Hansvedt Engineering, Inc., Urbana, IL; Part 2, Elox Division Colt Industries, Davidson, NC

*Linear corner wear ratio $= \frac{\text{electrode length}}{\text{workpiece length}} \times 100$. Includes end wear in this total wear ratio so figure provides length of electrode required for a finished length (depth) of workpiece

†Low-wear (pulse mode).

‡Wear ratios are for 90° corner. Less than 1% electrode wear is achieved, between 450 and 50 microseconds on-time with copper, and 250 to 35 microseconds on-time with graphite. Settings vary with electrode material

12.3 Electrical Discharge Machining—EDM

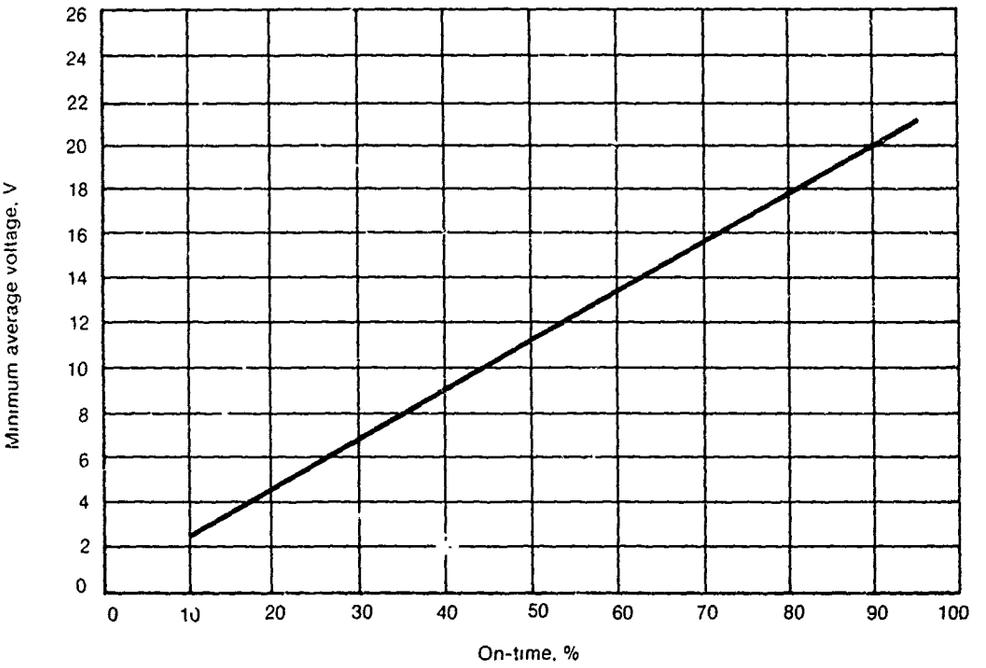


Figure 12.3–20 Voltage setting for EDM. (Courtesy of Hansvedt Engineering, Inc.)

TABLE 12.3–13 Electrode Manufacturing Methods

- Conventional machining from solid block; mill, drill, turn, etc.
- Cut off from bar stock, rounds, squares, shapes, extrusions
- Tracer milling from plaster master
- Punching
- Total form machining (TFM, see section 10.6)
- Electroforming
- Casting (die, investment, plaster)
- Rotating discs
- Molding (cold, powder metal)
- Pressing, forging, coining
- Extruding
- Electrical discharge wire cutting (EDWC, see section 12.5)

TABLE 12.3-14 Typical Equipment and Conditions for Machining Graphite

EQUIPMENT	ECONOMICAL TOLERANCES* (varying with size and volume)		SURFACE ROUGHNESS R_a		TOOL TYPE	MACHINE SETTINGS		FEED RATE
						Tool Speed		
	in	mm	μin	μm		ft/min	m/min	
Band saw	0.06 to 0 19	1.5 to 4.8	350 to 600	8 to 15	0.5 inch [12 7 mm] blade width— 4 teeth/inch [6 3 mm/pitch]	5,000	1,525	Feed by hand
36-grit silicon wheel	0 03 to 0 06	0.8 to 1.5	125†	3.2	Thickness 0.06 in [1.5 mm]	7,000	2,130	Feed by hand
Lathe	0.003 to 0 125	0.08 to 3.2	50 to 250	1.27 to 6.3	Radius tungsten-carbide tipped tools	850	260	0.008 to 0.018 inch [0.2 to 0.5 mm]
Drill	0.003 to 0.016	0.08 to 0.4	300 to 400	7.6 to 10	Tungsten carbide	110	34	Feed by hand
Mill	0.003 to 0.06	0.08 to 1.5	120 to 300	3.0 to 7.6	Fly cutter with 2 tungsten-carbide bits, 6-inch [150 mm] diameter	1,900	580	9 to 60 in/min [0.2 to 1.5 m/min]
Reamer	0.002 to 0.005	0.05 to 0.13	35 to 65	0.89 to 1.7	Tungsten-carbide reamer	80	24	0.01 in [0 25 mm] cut
Hone	0.001 to 0.003	0.03 to 0.08	20 to 32	0.5 to 0.8	400 to 800 grit	200	60	Force necessary
						Pressure		
						psi	kPa	
Lapping machine	0 001 to 0.003	0.03 to 0.08	15 to 30	0.4 to 0.8	No. 320 or higher grit aluminum oxide wheels	40	276	Grind for 1 minute (variable)

SOURCE Airco Speer, St Marys, PA

NOTE· Graphite is readily machinable and can be machined using normal metalworking equipment Power requirement for machining graphite is normally about half that required for steel Good dust collection equipment is a "must" when machining graphite, since large quantities of abrasive dust that are generated will cause wear to the moving parts of machinery Graphite is a brittle material and requires good-quality tools with sharp cutting edges to maintain tolerances Sharp internal corners should be avoided if possible since these set up stress points that can cause cracking.

*Finer tolerances can be maintained by carefully controlling operations when only a few parts are being machined

†Lower surface roughness values can be obtained by using finer-grit wheels

TABLE 12.3-15 Optimum Machining Parameters Used To Compare Mini-Rod™ Electrodes with Metallic Electrodes

ELECTRODE MATERIAL	ELECTRODE POLARITY	PEAK CURRENT A	PULSE/PAUSE TIME μs	FREQUENCY kHz	DUTY CYCLE percentage	GAP VOLTAGE V
Poco Mini-Rod™	Negative	12.5	12/100	8.93	11	50
Brass	Negative	25.0	200/800	1.00	20	50
Copper	Negative	25.0	100/800	1.11	11	50
Copper-tungsten	Positive	25.0	25/100	8.00	20	50
Tungsten	Positive	25.0	50/1600	0 60	3	50

SOURCE· Poco Graphite, Inc , Decatur, TX.

12.3 Electrical Discharge Machining—EDM

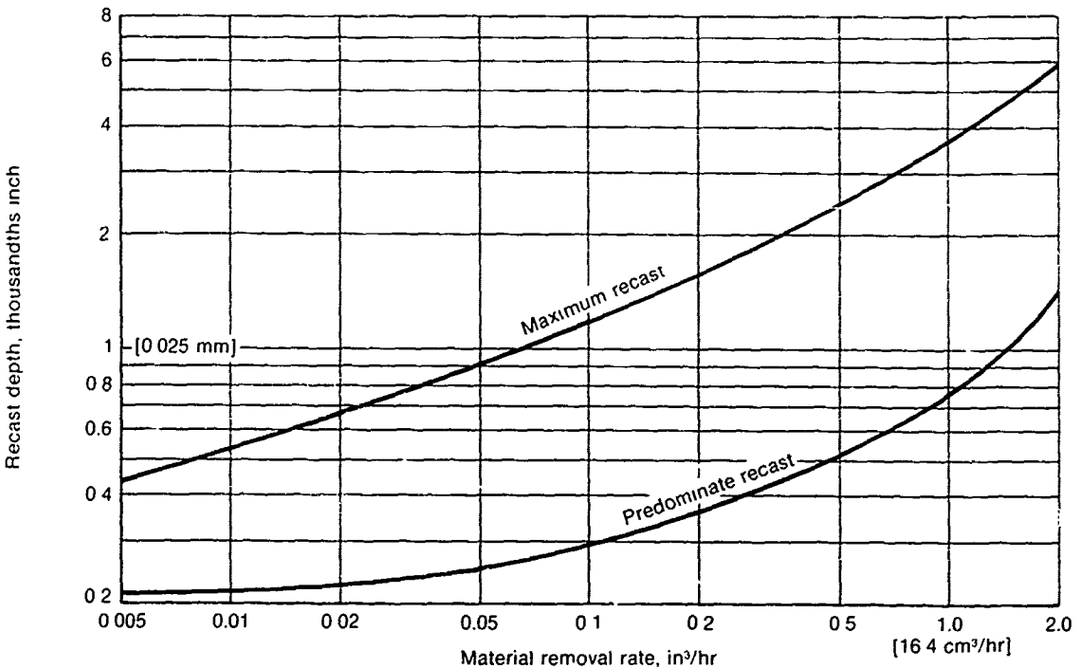


Figure 12.3-21 Depth of recast versus process intensity (material removal rate) for EDM of a variety of materials. (Modified from G Bellows, p. 19)

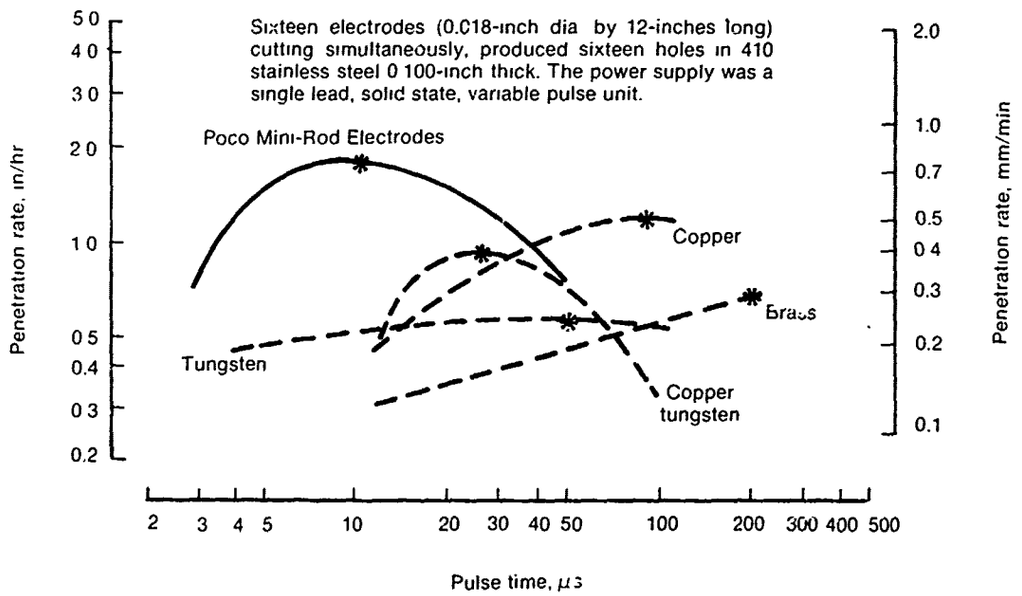
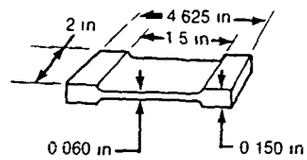
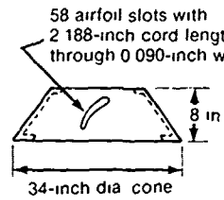
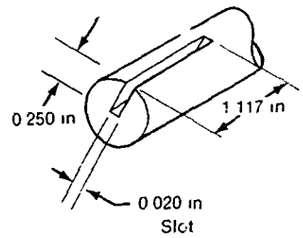


Figure 12.3-22 EDM drilling performance data for various electrode materials. (Courtesy of Poco Graphite, Inc.)

SPECIFIC APPLICATIONS DATA

TABLE 12.3–16 Specific Applications Data for Electrical Discharge Machining

Work material:	**Rene 80, STA**		**Hastelloy Alloy X**	**A6 Steel, 56 R_c**	
Workpiece configuration	 Fatigue test specimen				
Power supply:	Elox HPR104	Elox HPR104	Ingersoll Special	Hansvedt SM-150B	Hansvedt SM-150B
Electrode material:	copper (rotating wheel)	copper (rotating wheel)	copper punching (used once)	graphite rotating disc	graphite rotating disc
Dielectric type.	Texaco 499	Texaco 499	Eloxal 13 oil	spray flushing Hansvedt SE-290 oil	spray flushing Hansvedt SE-290 oil
pressure, psi:	0	0	submerged		
Operation type	roughing	finishing		roughing	finishing
Capacitance, μF:	2	0	30	0	0
Frequency, kHz:	16	250	8	10 (70% on)	250 (5% on)
Voltage (open circuit), V:	80	70		40	15
Average current, A:	4 to 5	1	25 to 30	4	2
Polarity on electrode	negative	negative	negative	positive	negative
Material removal rate, in^3/hr:					
Cutting time, min:sec.				24:00	9:00
Surface roughness, μin R_a:	205	90	no burrs		32
Tolerance, inch:	±0.001	±0.001	±0.002		
Overcut, inch/side:				0.003	0.0005
Taper, inch/side:					
Corner radii, inch/side.					
Linear wear ratio end:				<1%	0.002
corner:			15:1 by volume		
Notes:	45 strokes/min reciprocation.	45 strokes/min reciprocation.	4 electrodes simultaneously. Automatic index		

12.3 Electrical Discharge Machining—EDM

TABLE 12.3-16—Continued

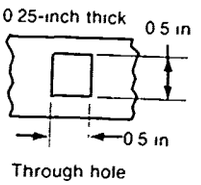
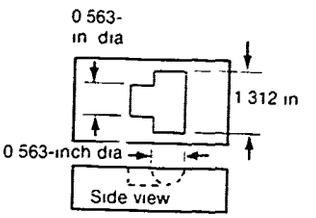
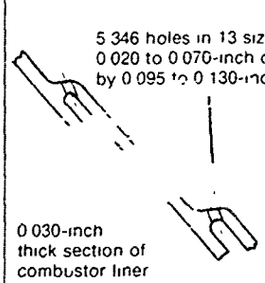
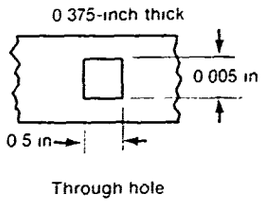
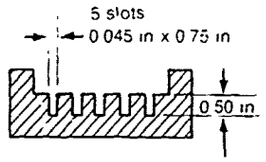
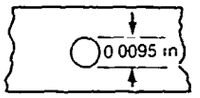
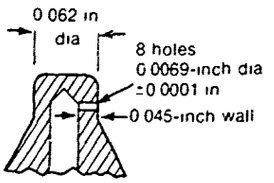
Work material	420 Stainless Steel				O1 Tool Steel	
Workpiece configuration	 Through hole				 Half of mold for fitting	
Power supply					Hansvedt SM-150B	Hansvedt SM-150B
Electrode material	graphite	brass	copper	zinc	copper	copper
Dielectric type	oil	oil	oil	oil	Hansvedt SE-290 oil	Hansvedt SE-290 oil
pressure, psi.						
Operation type					roughing	finishing
Capacitance, μF	24	24	24	16	0	0
Frequency, kHz:	16	16	16	16	2 (70% on)	
Voltage (open circuit), V.					25	80
Average current, A:	25	25	25	15	10	1
Polarity on electrode:	negative	negative	negative	negative	positive	positive
Material removal rate, in^3/hr:	0.40	0.34	0.38	0.21		
Cutting time, min sec:					156:00	48:00
Surface roughness, μin R_a.	210 to 270	170 to 210	210 to 240	200 to 230		24
Tolerance, inch.						
Overcut, inch/side:	0.002	0.003	0.0024	0.0034		
Taper, inch/side:						
Corner radii, inch/side:						
Linear wear ratio end: corner.	5.45	2.08	3.55	6.45		1%
Notes:					Ram cycling and pulse flush. One electrode for both roughing and finishing.	Ram cycling and pulse flush. One electrode for both roughing and finishing.

TABLE 12.3-16—Continued

Work material:	**Hastelloy Alloy X**	**H13 Tool Steel, 76 R_A**			
Workpiece configuration					
Power supply.	Raycon solid state 40-ampere split lead with refeed control	Elox PS50	Elox PS50	Elox PS50	Elox PS50
Electrode material:	copper-graphite and Poco EDMC-3	graphite (Gentrode 10)	graphite (Gentrode 10)	graphite (Gentrode 10)	graphite (Gentrode 10)
Dielectric type. pressure, psi:	Texaco 499 surface flow	petroleum oil 5	petroleum oil 5	petroleum oil 5	petroleum oil 5
Operation type.					
Capacitance, μF:	none	56	28	14	5
Frequency, kHz	10 (50 μs on-time; 50 μs off-time)	20	20	20	20
Voltage (open circuit), V·					
Current, A·	3	38	38	15	5
Polarity on electrode	negative	negative	negative	negative	negative
Material removal rate, $in^3/hr.$	0.11 in/min (7 to 26 holes/pass)	1.98	1.84	0.70	0.16
Cutting time, min:sec:	0:50	1:40	1.50	4:45	19:40
Surface roughness, μin R_a·	150 (approx. 0.001-inch recast)				
Tolerance, inch:	±0.002				
Overcut, inch/side.	0.002	0.0042	0.0040	0.0033	0.0019
Taper, inch/side:		0.0018	0.0016	0.0015	0.0012
Corner radii, inch/side:		0.013	0.010	0.007	0.005
Linear wear ratio end. corner·	15%	7.0 1.2	6.5 1.1	5.9 1.1	3.2 1.2
Notes:	Fully automatic multiple drilling with 3-axis NC control and multiple slides for electrode refeed cartridges. 11 holes average per pass.	⅜-inch diameter predrilled hole for flushing.	⅜-inch diameter predrilled hole for flushing.	⅜-inch diameter predrilled hole for flushing.	⅜-inch diameter predrilled hole for flushing.

12.3 Electrical Discharge Machining—EDM

TABLE 12.3–16—Continued

Work material	**Low Carbon Steel**	**C11 Carbide**	**7520 Heat-treated Steel**
Workpiece configuration.		 0 125-inch thick	 Fuel injector nozzle
Power supply·		Elox PT5	Raycon SH101
Electrode material·	graphite	tungsten wire	tungsten
Dielectric type.	petroleum oil	mineral oil	oil
pressure, psi·	10	0	
Operation type:			
Capacitance, μF:	0.25	0.90	
Frequency, kHz:		100	
Voltage (open circuit), V·	40		
Current, A:	2	0.2	
Polarity on electrode:	negative	negative	negative
Material removal rate, in^3/nr:	0.030	9×10^{-5}	
Cutting time, min:sec:	240:00	5:25	0.30 per hole
Surface roughness, μin R_a·	50		16 to 18, no burrs
Tolerance, inch:	±0 001		±0.001
Overcut, inch/side:	0.0007	0007	
Taper, inch/side:	±0.001	0.0002	>0.0002
Corner, radii, inch/side·			
Linear wear ratio end:			
corner:			
Notes:	One slot per stroke. Electrode reground 3 times per slot. Quill recycling used.		Automated fixture.

PROCESS SUMMARY

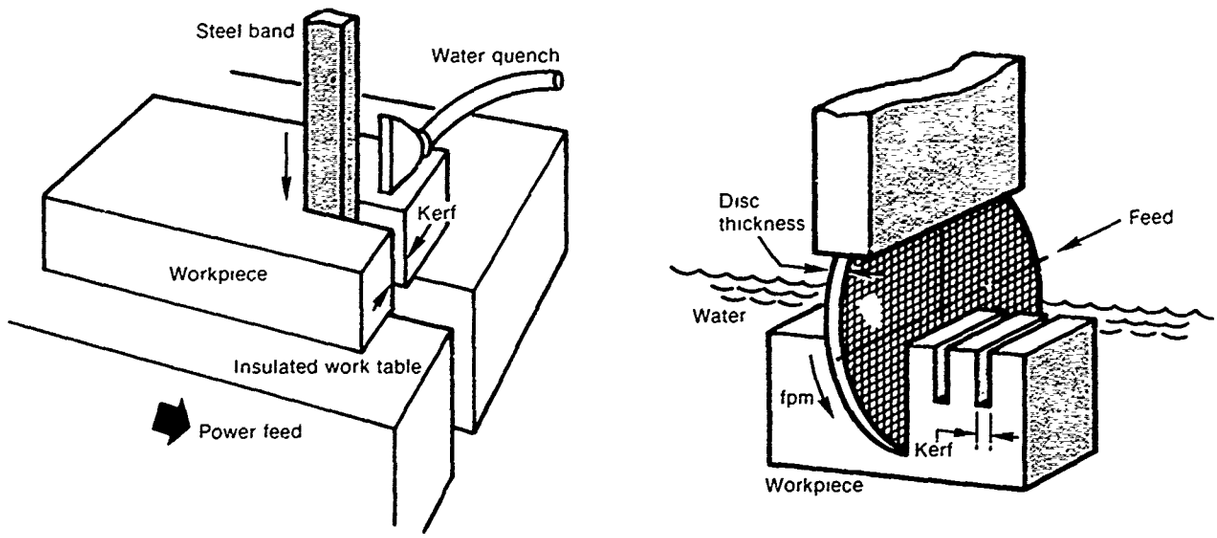


Figure 12.4–1 EDS schematic. *Left*, band saw: *right*, disc saw.

Principles

Electrical discharge sawing (EDS) is a variation of electrical discharge machining (EDM) that combines the motion of either a band saw or a circular disc saw with electrical erosion of the workpiece (see figure 12.4–1). The rapid-moving, untoothed, thin, special steel band or disc is guided into the workpiece by carbide-faced inserts. A kerf only 0.002- to 0.005-inch [0.050 to 0.13 mm] wider than the blade or disc is formed as they are fed into the workpiece. The feed can be (1) uniform with continuous arcing and constant feed or (2) servo-controlled to maintain a positive gap and arc control. The low-voltage, direct-current power supplies high currents to the gap, and water is used as a cooling quenchant for the tool, swarf and workpiece. Circular cutting is usually performed underwater, thereby reducing noise and fumes. While the work is power-fed into the band (or the disc into the work), it is not subjected to appreciable forces because the arc does the cutting, so fixturing can be minimal. Precision adjustment of the feed rate is made to be in exact balance with the arc erosion rate.

Practical Applications

EDS will cut any electrically conductive material or, simultaneously, a mixture of such materials. It will cut about twice as fast as a conventional abrasive saw and has a significantly smaller kerf. The low cutting forces permit slicing of fragile or cellular structures like honeycomb, and because erosion rates are independent of workpiece hardness, it easily cuts aluminum, stainless steel or titanium. No-burr cutting produces few or no roll-over edges on thin materials. Cuts up to 40-inches [1 m] deep have been made on thin-walled heat exchanger tubular assemblies. The low forces involved result in few tracking problems, and the total indicator runout (TIR) is low. Billet and bar cutoff is a natural application.

Operating Parameters

See table 12.4–1.

Material Removal Rates and Tolerances

Cutting rates are approximately proportional to the melting point of the workpiece material. The rate is independent of material hardness, but the material must be electrically conductive. When cutting steels, band EDS provides cutting rates of 5 to 20 square inches per minute [32 to 129 cm^2/min], while circular EDS runs from 20 to 300 square inches per minute [129 to 1935 cm^2/min] (see table 12.4–2). Straightness runs from ±0.003 inch [±0.076 mm] TIR at the lower feed rates to ±0.016 inch [±0.40 mm] TIR at the higher feed rates.

12.4 Electrical Discharge Sawing—EDS

TABLE 12.4–1 Typical Values for EDS Operating Parameters—Steel Workpieces

OPERATING PARAMETER	BAND EDS	DISC EDS
Power supply		
type:	Direct current	Direct current
voltage:	6 to 24 V	18 to 35 V
current (varies with thickness):	400 to 1,500 A	1,000 to 15,000 A
Fluids		
frequently	Water	Water
sometimes:	Air	Air
rarely:	Water glass (sodium silicate)	Water glass (sodium silicate)
Fluid flow:	5 to 13 gal/min [20 to 50 L/min]	Submerged
Speed of band or disc:	5,000 to 6,000 fpm [1,525 to 1,830 m/min]	6,000 to 8,000 fpm [1,830 to 2,440 m/min]
Thickness of band or disc:	0.020 to 0.030 inch [0.50 to 0.76 mm]	0.025 to 0.20 inch [0.64 to 5.1 mm]
Width of band or disc diameter:	0.5 to 1.25 inch [12.7 to 31.8 mm]	Up to 50-inch dia. [up to 1.25 m dia.]
Wear ratio, workpiece-to-band or workpiece-to-disc:	Approx. 3:1	Approx. 10:1
Cutting rates:	5 to 20 in^2/min [32 to 129 cm^2/min]	20 to 300 in^2/min [129 to 1,935 cm^2/min]
Surface roughness, R_a		
coarse, high-ampere cutting:	400 to 500 μin [10 to 12.5 μm]	400 to 500 μin [10 to 12.5 μm]
fine, low-ampere cutting:	250 to 400 μin [6.3 to 10 μm]	250 to 400 μin [6.3 to 10 μm]

TABLE 12.4–2 Circular Arc Saw Cutting Rates

WORK MATERIAL	CUTTING RATE	
	in^2/min	cm^2/min
Aluminum	775	5,000
Tool steel	280	1,800
Stainless steel	263	1,700
Nickel alloys	280	1,800
Cobalt alloys	280	1,800

Surface Technology

Surface roughness values for EDS are usually greater than those for conventional band sawing or abrasive cutoff. Typically, values range from 400 to 500 microinches R_a [10 to 12.5 μm] for high feed rates and 250 to 400 microinches R_a [6.3 to 10 μm] for low feed rates. The arc discharges leave a recast and heat-affected zone on the surface that is 0.001-to 0.005-inch [0.025 to 0.13 mm] deep.

Equipment and Tools

Tooling consists of simple holding devices because only low forces are involved. Good electrical contact is needed. Band arrangements are available with throats up to 48-inches [1.2 m] deep. Discs with 18- to 60-inch [0.5 to 1.5 m] blades are typical, with blades up to 72-inches [1.8 m] diameter available on special order. Current capacities up to 15,000 amperes have been used.

Machining Characteristics

Fast, narrow-kerf, single-plane cutting is available. Both noise and fume pollution can be reduced when EDS is carried out underwater. Clean, easily recovered swarf aids recycling of expensive metals. Arc erosion also occurs on the blade or disc.

Electrical Discharge Wire Cutting—EDWC 12.5

PROCESS SUMMARY

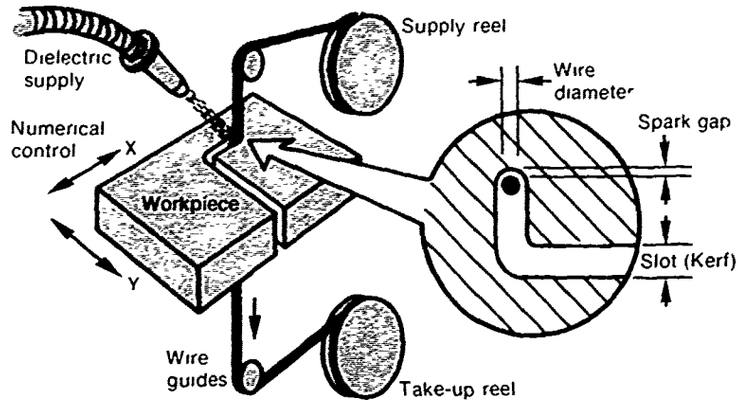


Figure 12.5–1 EDWC schematic.

Principles

Electrical discharge wire cutting (EDWC) is a special form of electrical discharge machining wherein the electrode is a continuously moving conductive wire (see figure 12.5-1). EDWC is often called traveling-wire EDM. A small-diameter, tensioned wire is guided to produce a straight, narrow-kerf cut. The slowly moving wire brings a fresh, constant-diameter electrode to the cutting gap, thereby enhancing kerf size control. Usually, a programmed or numerically controlled motion guides the cutting, while the width of the kerf is maintained by the wire size and discharge controls. The dielectric is oil or deionized water carried into the gap by motion of the wire. The wire is inexpensive enough to be used only once. The cutting is basically a two-axis process.

Practical Applications

EDWC acts like an electrical band saw with the wire replacing the band and the spark discharge, the teeth. A straight cut perpendicular to the major axis of the workpiece has no flaring or bellmouth, and extremely tight corners can be cut with almost no radius. Punches, dies and stripper plates can be cut in any of the hardened, conductive tool materials. The same NC tape can be used repeatedly for short production runs. Mirror-image profile work and internal contours from a starting hole are frequent. Stacking of sheets for multiple cutting is possible. Conventional carbide dies can frequently be cut from a solid plate using EDWC, without the conventional segmenting and fitting. Operation without an attendant is a regular practice, and operating time has extended to as much as 50 hours of cutting with one reel of wire.

Operating Parameters

TABLE 12.5–1 Typical Values for EDWC Operating Parameters

Power supply	
type:	55 to 60 V (open circuit volts to 300)
frequency:	Pulse time controlled 1 to 100 μs in time or 180 to 300 kHz with 3 kHz most frequent
current:	1 to 32 A
Electrode wire	
types:	Brass, copper, tungsten, molybdenum
diameter:	0.003 to 0.012 inch [0.076 to 0.30 mm]; most frequently used size is 0.008 inch [0.2 mm]
speed:	0.1 to 6 in/s [2.5 to 150 mm/s]
Dielectric:	Deionized water, oil, or rarely, air, gas or plain water
Overcut (working gap):	0.0008 to 0.0020 inch [0.02 to 0.05 mm]; usually 0.001 inch [0.025 mm]

12.5 Electrical Discharge Wire Cutting—EDWC

Material Removal Rates and Tolerances

Cutting of 0.001- to 6-inch [0.25 to 150 mm] thick materials can be done at a rate of approximately 1 square inch per hour [6.5 cm^2/hr], which on thin parts can yield cutting at 40 inches per minute [1 m/min] (see tables 12.5-2 and 12.5-3). Positioning accuracy up to ±0.0001 inch [±0.0025 mm] is normal in all metals. Workpiece accuracy usually is ±0.0005 inch [±0.013 mm], with special instances of ±0.0002 inch [±0.005 mm] and ±0.0001 inch [±0.0025 mm] in unique applications.

Surface Technology

Surface roughness is typically in the 30- to 50-microinch R_a [0.8 to 1.3 μm] range, and the surface has a matte or velvet-like texture. Special care and slower cutting can produce a surface roughness of 15 microinches R_a [0.4 μm]. The recast and the heat-affected zone are very small and uniform with the low spark energy levels that are typically used. These layers should be removed or modified on critical or fatigue-sensitive surfaces.

Equipment

Several manufacturers regularly build EDWC equipment with NC, tracer controls and all programming accessories. Die relief angle generators and offset controls are available on most machines along with kerf-width control via the gap setting and wire-diameter selection. Equipment is also available with cam or other mechanical programming for the wire motion as well as with standard EDM servo control for straight cutting.

Some machines have CNC or optically guided motion direct from an enlarged drawing. Table motions as much as 2 by 3 feet [0.6 by 1 m] have been made, with 1 by 1 foot [0.3 by 0.3 m] being more common. Workpiece thickness 3 to 6 inches [75 to 150 mm] can be accommodated.

Forces are low, so simple holding fixtures are practical. A 5-pound [2.25 kg] reel of 0.008-inch [0.2 mm] diameter copper wire can provide 36 hours of cutting.

Machining Characteristics

The machine motions are similar to those for a band or a wire saw. Use of cutter offset control permits several sizes to be cut from the same NC tape. The cutting accuracy is high because the spark erosion emanates from a fresh, constant-size section of wire.

SELECTED DATA

TABLE 12.5-2 Average Performance Data For EDWC with Brass Wire Electrode

WORKPIECE MATERIAL	WIRE DIAMETER in [mm]	WORK THICKNESS, H in [mm]	CUTTING WIDTH, S in [μm]	SURFACE ROUGHNESS, R_z (Ten-Point Height) μin [μm]	REMOVAL RATE, Vs in³/min [cm³/min]
Steel carbon chrome	0.004 [0.1]	0.08 to 0.80 [2 to 20]	0.005 [130]	8 to 12 [0.2 to 0.3]	0.0109 [0.070]
	0.006 [0.15]	0.08 to 2.0 [2 to 50]	0.0078 [198]	14 to 20 [0.35 to 0.5]	0.0186 [0.120]
	0.008 [0.2]	0.08 to 3.0 [2 to 75]	0.0102 [259]	14 to 28 [0.35 to 0.71]	0.0388 [0.250]
	0.010 [0.25]	0.4 to 5.0 [10 to 125]	0.0134 [340]	14 to 28 [0.35 to 0.71]	0.0388 [0.250]
	0.012 [0.3]	3.0 to 6.0 [75 to 150]	0.0149 [378]	14 to 20 [0.35 to 0.5]	0.0388 [0.250]
Copper	0.010 [0.25]	0.08 to 1.6 [2 to 40]	0.0126 [320]	14 to 28 [0.35 to 0.7]	0.03 [0.194]

SOURCE Agietron Corporation
NOTE To calculate cutting speed divide removal rate (Vs) by work thickness (H)

12.5 Electrical Discharge Wire Cutting—EDWC

TABLE 12.5-2 — Continued

WORKPIECE MATERIAL	WIRE DIAMETER in [mm]	WORK THICKNESS, H in [mm]	CUTTING WIDTH, S in [mm]	SURFACE ROUGHNESS, R_z (Ten-Point Height) [μm]	REMOVAL RATE, Vs in²/min [cm²/min]
Carbide 15% cobalt	0.004 [0.1]	0.08 to 0.8 [2 to 20]	0.0075 [190]	6 to 9 [0.15 to 0.24]	0.0054 [0.035]
	0.006 [0.15]	0.08 to 1.2 [2 to 30]	0.009 [229]	9 to 11 [0.24 to 0.28]	0.011 [0.071]
	0.010 [0.25]	0.08 to 2.0 [2 to 50]	0.0142 [361]	8 to 20 [0.2 to 0.5]	0.019 [0.122]
Graphite	0.010 [0.25]	0.08 to 1.6 [2 to 40]	0.0139 [351]	14 to 24 [0.35 to 0.6]	0.0186 [0.120]
Aluminum	0.010 [0.25]	0.08 to 1.6 [2 to 40]	0.0134 [340]	20 to 35 [0.5 to 35]	0.093 [0.60]

SOURCE: Agietron Corporation

NOTE: To calculate cutting speed, divide removal rate (Vs) by work thickness (H).

TABLE 12.5-3 Average Performance Data for EDWC with Molybdenum Wire Electrode

WORKPIECE MATERIAL	WIRE DIAMETER in [mm]	WORK THICKNESS, H in [mm]	CUTTING WIDTH, S in [μm]	SURFACE ROUGHNESS, R_z (Ten-Point Height) μin [μm]	REMOVAL RATE, Vs in²/min [cm²/min]
Steel, carbon chrome	0 003 [0 08]	0.08 to 0.4 [2 to 10]	0 004 [105]	14 to 22 [0 35 to 0 55]	0 0078 [0 05]
	0 004 [0 1]	0 08 to 0.4 [2 to 10]	0 0049 [125]	18 to 23 [0.47 to 0 59]	0 0109 [0 07]
Carbide, 15% cobalt	0.003 [0.08]	0 08 to 0.5 [2 to 12 7]	0 004 [105]	3 to 9 [0 078 to 0 23]	0 0062 [0 04]
	0 004 [0 1]	0.08 to 0 5 [2 to 12 7]	0 0053 [135]	5 to 9 [0 118 to 0 23]	0.0093 [0 06]

SOURCE Agietron Corporation
NOTE To calculate cutting speed, divide removal rate (Vs) by work thickness (H)

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Laser Beam Machining—LBM 12.6

PROCESS SUMMARY

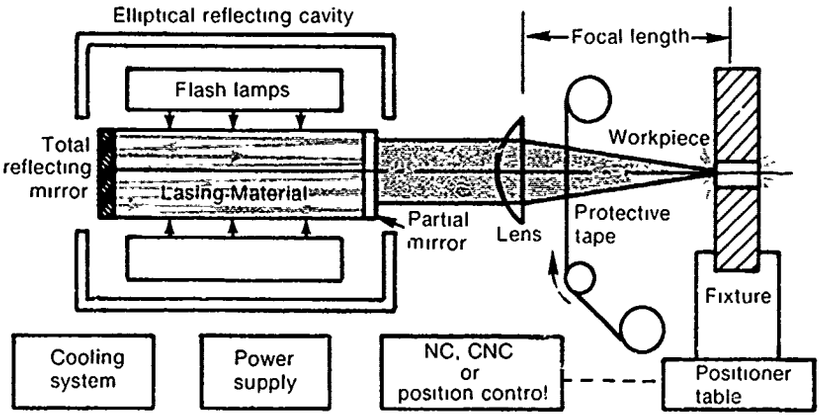


Figure 12.6-1 LBM schematic.

Principles

Laser beam machining (LBM) removes material by melting, ablating, and vaporizing the workpiece at the point of impingement of a highly focused beam of coherent monochromatic light (see figure 12.6-1). Laser is an acronym for "Light Amplification by Stimulated Emission of Radiation." The electromagnetic radiation operates at wavelengths from the visible to the infrared (see table 12.6-3). The principal lasers used for material removal are the neodymium-glass, the Nd-YAG (neodymium-yttrium aluminum garnet), the ruby and the carbon dioxide (CO_2). The last is a gas laser (most frequently used as a torch with an assisting gas—see LBT, laser beam torch), while the others are solid state lasing materials.

For pulsed operation, the power supply produces short, intense bursts of electricity into the flash lamps, which concentrate their light flux on the lasing material. The resulting energy from the excited atoms is released at a characteristic, constant frequency. The monochromatic light is amplified during successive reflections from the mirrors. The thoroughly collimated light exits through the partially reflecting mirror to the lens, which focuses it on or just below the surface of the workpiece. The small beam divergence, high peak power and single frequency provide excellent, small-diameter spots of light with energy densities up to 3×10^{10} watts per square inch [4.6×10^9 W/cm^2] which can sublime almost any material. Cutting requires energy densities of 10^7 to 10^9 watts per square inch [1.55×10^6 to 1.55×10^8 W/cm^2], at which rate the thermal capacity of most materials cannot conduct energy into the body of the workpiece fast enough to prevent melting and vaporization. The initial or leading edge of the power spike is most important in CO_2 lasers to initiate vaporization in nonmetal drilling, which then promotes better absorption of the energy. Workpiece surface reflectivity, absorption coefficient, thermal conductivity, specific heat and heat of vaporization are all important when considering a laser application.

Cutting, welding, scribing and heat treating can all be done with the same laser by varying the energy density and by appropriately adjusting the focus (spot size) and the pulse duration. Sharp, short, Gaussian-mode repetitive pulses are best for cutting because they have high energy densities. Welding requires longer duration pulses and a broad spot. Welding energy densities are 10^5 to 10^7 watts per square inch [1.55×10^4 to 1.55×10^6 W/cm^2]. Heat treating operates at under 10^6 watts per square inch [1.55×10^5 W/cm^2], and scribing requires very short cutting pulses (see figures 12.6-3 to 12.6-7). Heat treating and welding are not covered in this process summary.

During laser beam machining, the expulsed material forms metal gases and vapors, which subsequently solidify to dust or minute beads. In addition to protection for the lens from molten particles or splatter, a "chip" removal system—frequently a vacuum cleaner type—is desirable to keep the operating area clean and free from dust.

Practical Applications[1]

LBM is not a mass material removal process—it is a fast, easily controlled process with a non-contact, non-wearing tool that imparts minimal heat and thermal distortion with minimal demands upon fixturing. The high energy density in a well-focused beam will melt and vaporize any material. Contour cuts and slitting of thin steels, aluminum, titanium alloys, and other metals are done at rapid rates with narrow kerfs; continuous-wave (CW) modes or high pulse rates are used. Texturing and etching are performed at lower energy levels. Small hole drilling can be done at shallow angles (15 degrees) to the surface. Multiple pulses permit

[1]Laser technology is advancing so rapidly that current limitations frequently are removed by more recent developments. A check with active laser-equipment builders is recommended for new applications.

12.6 Laser Beam Machining—LBM

hole drilling to 40:1 depth-to-diameter ratios on 0.005-inch [0.13 mm] diameter holes, while larger holes, 0.050-inch [1.27 mm] diameter, can be drilled in 0.50-inch [12.7 mm] thick material. Trepanning is done for still larger holes using NC or a circle-generator attachment. Plastics, rubber, cloth and similar organic-base materials cut more easily than the metals. Ceramics, glasses and composites of many types are drilled, scribed and diced. Microcircuit components, resistor trimming or circuit "deburring" make use of the laser's speed and precision. Viable applications for LBM range from diamond wire draw dies to catheter drilling to food sieves. The ability to direct and focus the laser beam into inaccessible locations permits unusual applications, such as balancing rotors dynamically while they are rotating.

For additional applications, see Laser Beam Torch, section 12.7—particularly for slitting and for contour cutting

Operating Parameters

TABLE 12.6-1 Typical Values for LBM Operating Parameters and Process Capabilities

OPERATING PARAMETERS				
Lasing material:	Ruby	Nd-YAG	Nd-glass	CO_2
Type:	Solid state, smallest spot, high peak watts, most easily absorbed by metals	Solid state	Solid state	Gas, high efficiency
Composition:	0.03 to 0.07% Cr	1% Nd	Glass + 2 to 6% Nd	$CO_2 + He + N_2$
Wavelength, micrometers (see figure 12.6-8):	0.69	1.064	1.064	10.6
Efficiency, %:	Up to 1	2	2	10 to 15
Beam mode:	Pulse	Pulse or continuous	Pulse	Pulse or continuous
Spot size at focal point, in: [mm]:	0.0005 [0.013]	0.0005 [0.013]	0.001 [0.025]	0.003 [0.076]
Pulse repetition rate, pps* (normal mode operation):	1 to 10	1 to 300 or continuous wave	1 to 3	Continuous wave
Beam output, watts:	10 to 100	10 to 1,000	10 to 100	250 to 10,000
Peak power, kW (see figure 12.6-9):	200	400	200	100
Beam divergence, milliradians:	5 to 7	1 to 5	5 to 7	0.1 to 10
Excitation sources:	Krypton, xenon or tungsten-halogen lamps, electrical discharge			

PROCESS CAPABILITIES†	
Drilling diameter:	0.00002 to 0.050 inch [0.005 to 1.27 mm] (larger with trepanning)
Drilling depth:	Up to 0.70 inch [17 mm]
Drilling angle to surface:	15 to 90 degrees
Drilling taper:	5 to 20% of hole diameter
Drilling length-to-diameter ratio:	Up to 50:1
Drilling length, trepanned:	Up to 0.25 inch [6.4 mm]
Drilling tolerance:	±5 to 20% of hole diameter
Minimum corner radius:	0.010 inch [0.25 mm]

*pps = pulses per second. Q-switched lasing can greatly increase all these repetition rates.

†See also table 12.6-3 and figures 12.6-10 to 12.6-14.

Material Removal Rates and Tolerances

Material removal rates are slow, approximately 4 x 10^{-4} cubic inches per hour [6.5 x 10^{-3} cm^3/hr]. Nevertheless, a laser can drill or slot thin materials faster than a workpiece can be repositioned by numerical control. Even if multiple laser pulses are necessary, each pulse typically takes only one-thousandth second. The removal rates are inversely proportional to the material thickness. Even deeper holes can be drilled rapidly, for example, 1 to 3 seconds for a 0.020-inch [0.50 mm] diameter hole in 0.10-inch [2.5 mm] thick nickel alloy. Because flash lamps have a long life, costs can be reduced to a few cents per slot, and for multiple arrays of holes, to tenths-of-a-cent per hole. Holes and slots will have irregular surfaces or roundness and will contain taper, yet location accuracies up to ±0.001 inch [±0.025 mm] are commonplace and limited primarily by the accuracies available in the positioning devices for the workpiece. Conventional, axicon or toric lenses are used to attain better productivity in unusual applications.

Surface Technology

Laser machined surfaces are usually rough and have a recast texture. The rapidity of the application of energy reduces the heat-affected zone and recast to less than that from other thermal processes. The usual recast is about 0.001- to 0.002-inch [0.025 to 0.050 mm] thick, with some as much as 0.010 inch [0.25 mm], with a heat-affected zone below the recast, as shown in figure 12.6-13. In many materials, a hardness alteration will also occur below the surface. These surface effects can be detrimental to product integrity if the surface is highly stressed or if fatigue life is a concern. Removal or modification of such lasered surfaces is recommended (see section 18.3).

Equipment and Tooling

The principal equipment emphasis is the control of the position of the workpiece under the focal point of the beam. Multiple-axis control is needed to allow the beam to follow undulations in the workpiece. Computer or numerical control makes use of the easy integration of the laser parameters—intensity, focus, pulse rate—with motion control or automation. Beam deflecting, beam splitting for multiple machining sites, circle generators for trepanning, special lenses (toric, axicon), rotating mirrors, and time sharing are all employed in special laser systems. The absence of mechanical contact, the low-inertia beam and the nearly forceless characteristics of the laser simplify the fixturing.

Machining Characteristics

The ease with which the laser beam can be manipulated enhances its versatility. Adequate eye protection is needed for both direct and reflected laser light. The United States Bureau of Radiological Health has issued requirements that laser manufacturers should follow to assure personnel safety. The CO_2 laser wavelength is opaque to plastic, so shielding or enclosure is simplified. Dust control is necessary, and vacuum systems are the prevalent method for removing the "chips." The gases released by some materials during LBM should be checked with OSHA for safety effects.

12.6 Laser Beam Machining—LBM

SELECTED DATA

There are several valid techniques for selecting operating parameters for LBM. The steps in table 12.6-2 are recommended as one logical sequence. Supporting data come from the other figures and tables in accordance with the terms as explained in figure 12.6-2.

TABLE 12.6-2 Steps To Select LBM Operating Parameters

ITEM	DATA
1. Workpiece material and its thermal characteristics	Engineering drawings, specifications, handbooks
2. Select type laser, wavelength, and mode of operation	Tables 12.6-3 to 12.6-5 and figures 12.6-3 to 12.6-9.
3. Type optics	Small spot size, easier with shorter wavelengths; better quality optics required with longer wavelengths
4. Lens selection	Depth of focus (d), focal length (f), and spot size (s) determined on application need and configuration of workpiece
5. Workpiece motion control	CNC, DNC, or NC depending on complexity of workpiece and volume of production
6. Safety shields	Determined by material handling needs*

*See also D. Sliney, Health hazards from laser material processing, Technical paper MR75-581, Society of Manufacturing Engineers, Dearborn, MI, 1975.

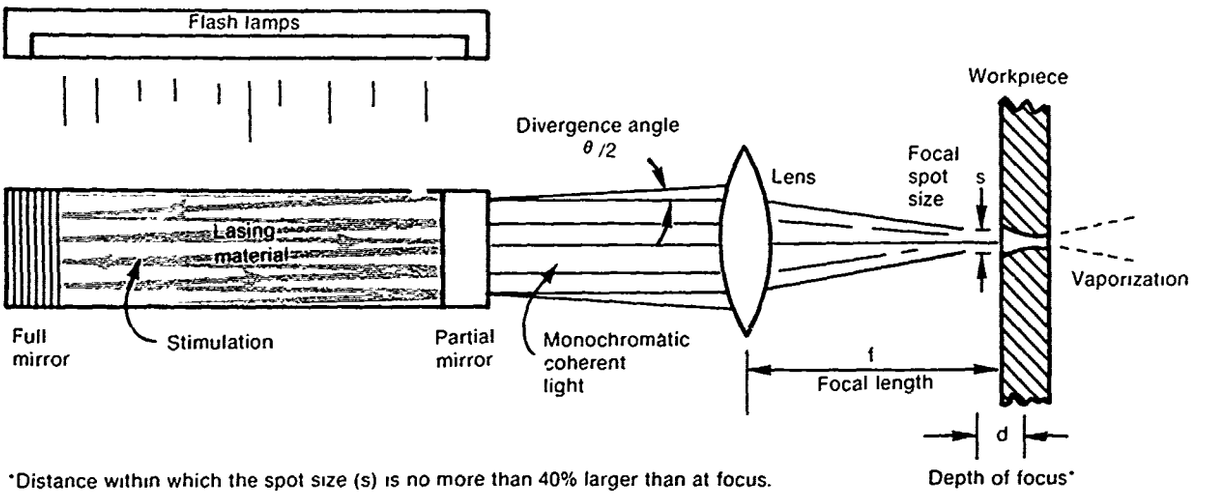


Figure 12.6–2 LBM parameter terminology.

TABLE 12.6–3 Commercial Lasers Suitable for Materials Processing

LASER TYPE	WAVELENGTH μm	MODE OF OPERATION	POWER W	PULSE REP. RATE pps	PULSE LENGTH	APPLICATION	COMMENTS
Argon	0.4880 0.5145	Repetitively pulsed	20 peak; 0.005 average	60	50 μs	Scribing thin films	Power low
Ruby	0.6943	Normal pulse	2×10^5 peak	Low (5 to 10)	0.2 to 7 ms	Large material removal in one pulse, drilling diamond dies, spot welding	Often uneconomical
Nd-Glass	1.06	Normal pulse	2×10^6 peak	Low (0.2)	0.5 to 10 ms	Large material removal in one pulse	Often uneconomical
Nd-YAG*	1.06	Continuous	1,000	—	—	Welding	Compact; economical at low powers
Nd-YAG	1.06	Repetitively Q-switched	3×10^5 peak; 30 average	1 to 24,000 300	50 to 250 ns 50 ns	Resistor trimming, electronic circuit fabrication	Compact and economical
Nd-YAG	1.06	Normal pulsed	400	300	0.5 to 7 ms	Spot weld, drill	
CO_2†	10.6	Continuous	15,000	—	—	Cutting organic materials, oxygen-assisted metal cutting	Very bulky at high powers
CO_2	10.6	Repetitively Q-switched	75,000 peak 1.5 average	400	50 to 200 ns	Resistor trimming	Bulky but economical
CO_2	10.6	Superpulsed	100 average	100	100 μs and up	Welding, hole production, cutting	Bulky but economical

SOURCE: Modified from J. F. Ready, Selecting a laser for material working, *Laser Focus* (March 1970), p. 40.

*Neodymium-yttrium aluminum garnet.

† CO_2 plus He plus N_2 mixture.

12.6 Laser Beam Machining—LBM

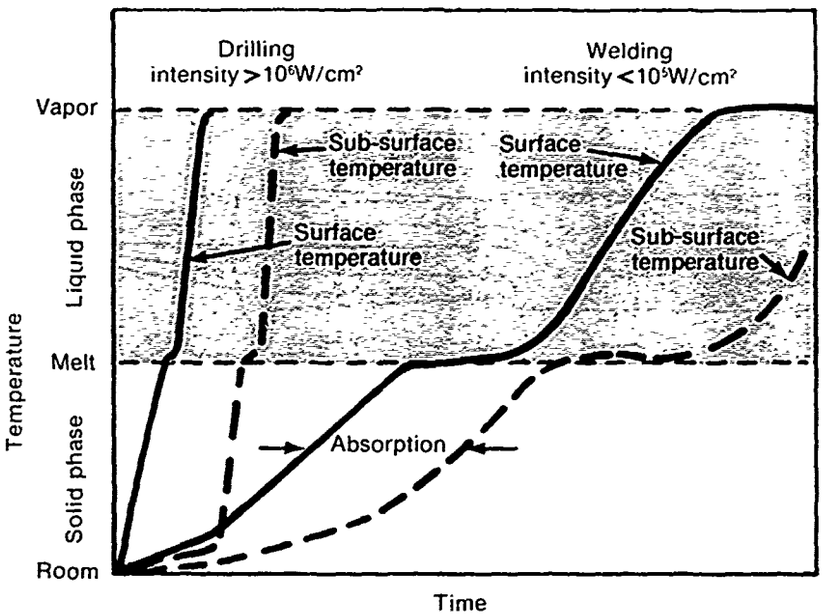
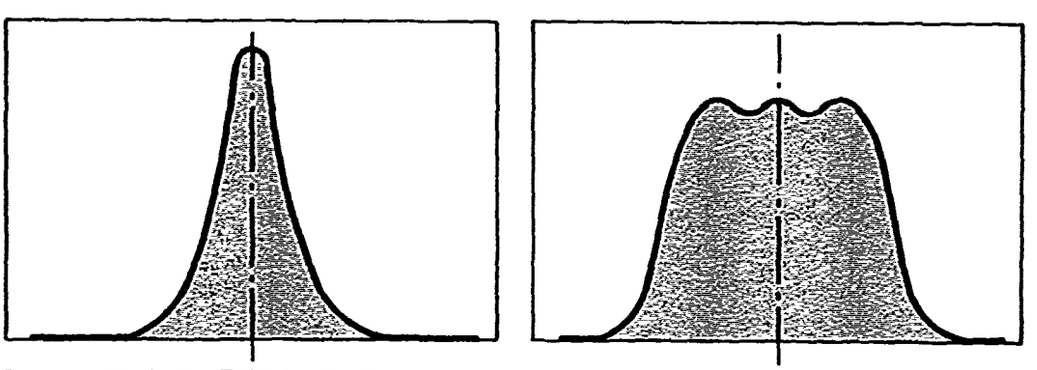


Figure 12.6–3 Difference in energy and absorption between laser drilling and laser welding. (S. R. Bolin, Pulsed-laser metalworking, *American Machinist* 120 (October 1976) p. 124)



Gaussian Mode (or TEM_{oc})*. Ideally suited for high quality cutting. Power densities up to 10^9 watts/inch² [1.55 x 10^3 W/cm²]. Mode quality is maintained throughout the power range.

Mixed Mode (approximately 50% each of TEM_{oo} and TEM_{01}). Flat topped distribution makes this model ideal for welding and heat treating.

*TEM — transverse excitation mode

Figure 12.6–4 Laser excitation modes for cutting versus welding. (Courtesy of GTE-Sylvania)

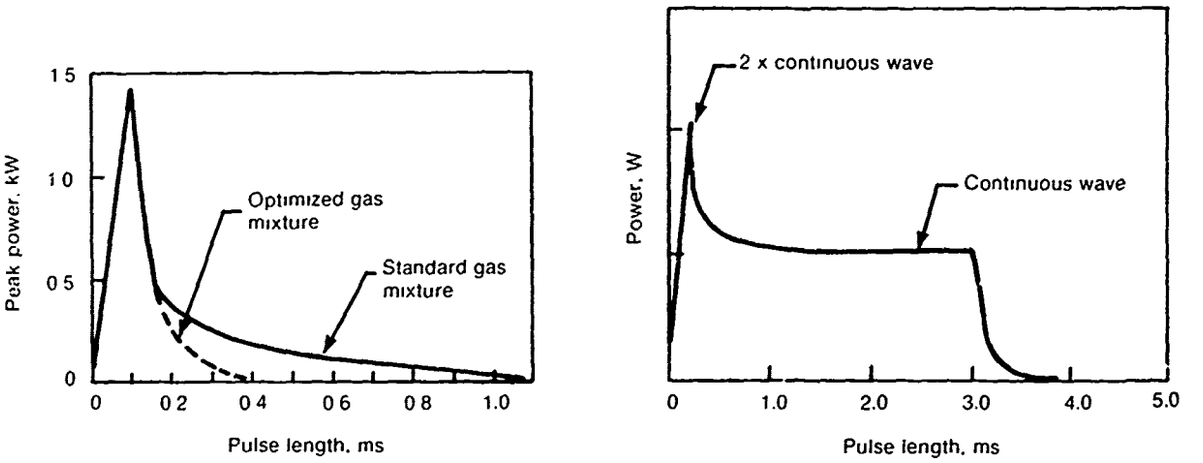


Figure 12.6–5 Pulse configurations for CO_2 lasers. *Left*, short pulse length (less than 100 μs to peak); *right*, long pulse length. (Courtesy of Coherent, Inc.)

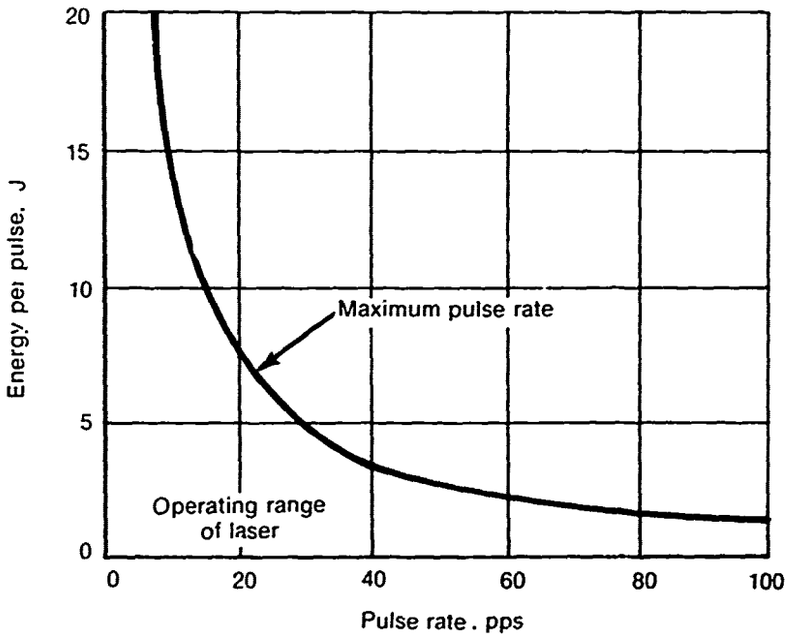


Figure 12.6–6 Operating range of a flash-lamp pulsed Nd-YAG laser. (Courtesy of Coherent, Inc.)

12.6 Laser Beam Machining—LBM

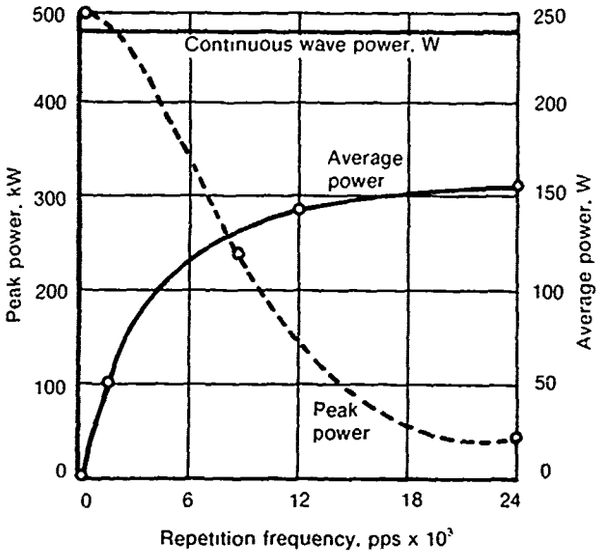


Figure 12.6-7 Relationship of peak power and average power with variation in repetition frequency (YAG laser). (Courtesy of Holobeam Laser Company)

TABLE 12.6–4 Relative Power To Vaporize Equal Volumes in Equal Time

Aluminum	1.0
Titanium	1.5
Iron	1.8
Molybdenum	2.2
Tungsten	2.9

SOURCE: *Metals Handbook: Vol. 3—Machining*, Metals Park, OH: American Society for Metals, 1967, p. 254.

TABLE 12.6–5 Selecting a Laser Type for Machining

APPLICATION	LASER TYPE
Large holes (to 0.060-inch [1.52 mm] diameter)	Ruby, Nd glass, Nd-YAG
Larger holes (trepanned)	Nd-YAG, CO_2
Small holes (>0.010-inch [0.25 mm] diameter)	Ruby, Nd glass, Nd-YAG
Drilling (punching or percussion)	Nd-YAG, Ruby
Thick cutting	CO_2 + gas assist*
Thin slitting metals	Nd-YAG
Thin slitting plastics	CO_2
Plastics	CO_2
Metals	Nd-YAG, Ruby, Nd glass
Organics, nonmetals	Pulsed CO_2
Ceramics	Pulsed CO_2, Nd-YAG

*See also gas-assisted cutting under LBT, section 12.7.

This nomograph provides fast, convenient conversions among the various ways of describing light waves in energy, frequency and wavelength

As an example, the left side of the nomograph shows that the 532-nanometer wavelength of a frequency-doubled neodymium-yag laser corresponds to an optical carrier frequency of 5 6 x 10^{14} hertz, and a photon energy of 2 3 electronvolts or 18,800 wavenumbers (cm^{-1})

The right side of the nomograph shows that the laser's spectral width of 0.5 cm^{-1} is equivalent to a width of 15 gigahertz or 0.14 angstrom.

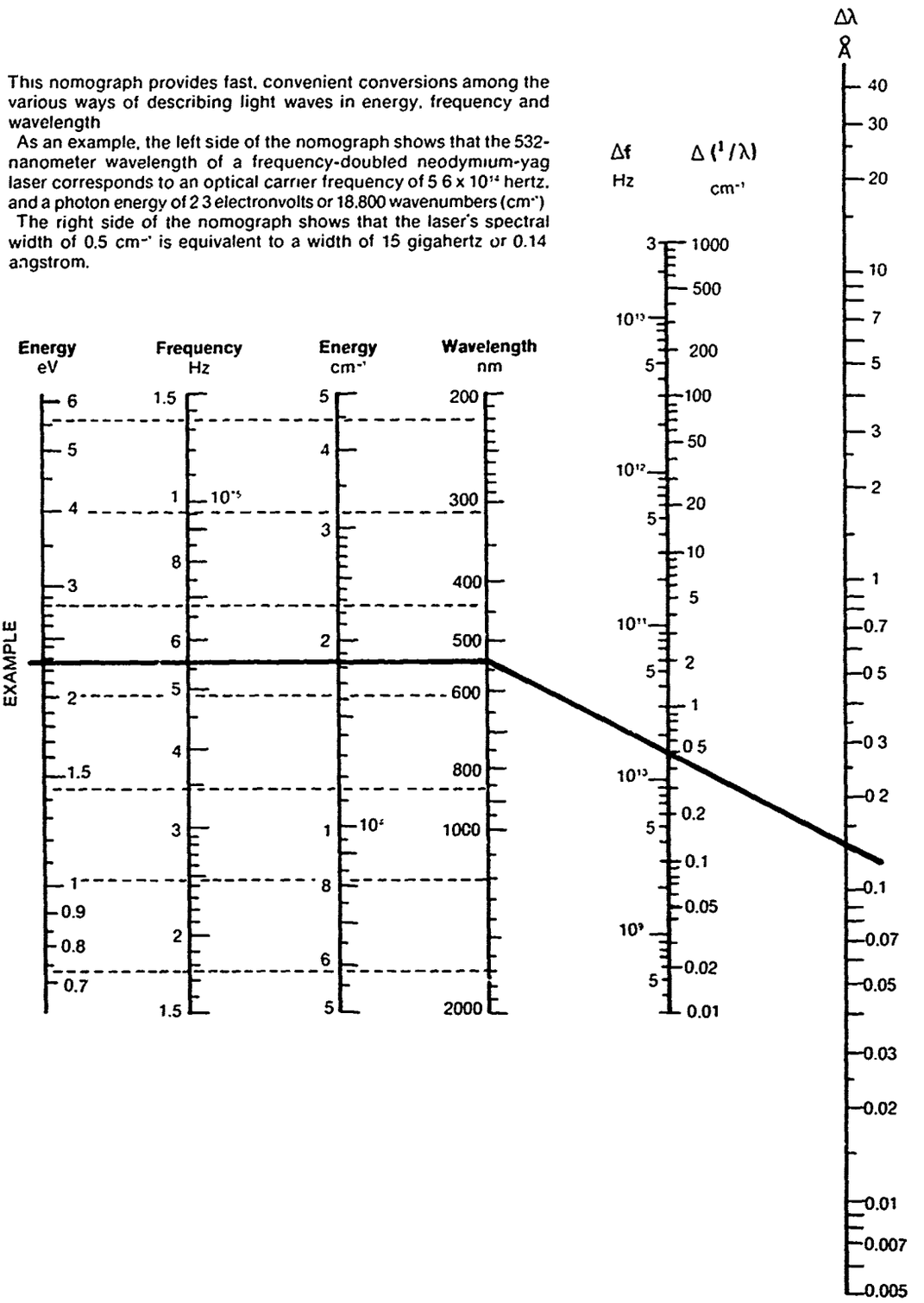


Figure 12.6-8 Energy nomograph. (Courtesy of Photonetics Associates; reprinted from 1979 *Laser Focus Buyers' Guide*)

12.6 Laser Beam Machining—LBM

This nomograph relates the energy and power of a laser beam to its temporal characteristics. In the example, the right side of the nomograph shows that a 50 nanosecond pulse containing 20 millijoules has a peak power of 400 kilowatts. the left side shows that, for the 20 mJ pulse, a pulse repetition frequency of 10 hertz corresponds to an average power of 200 milliwatts.

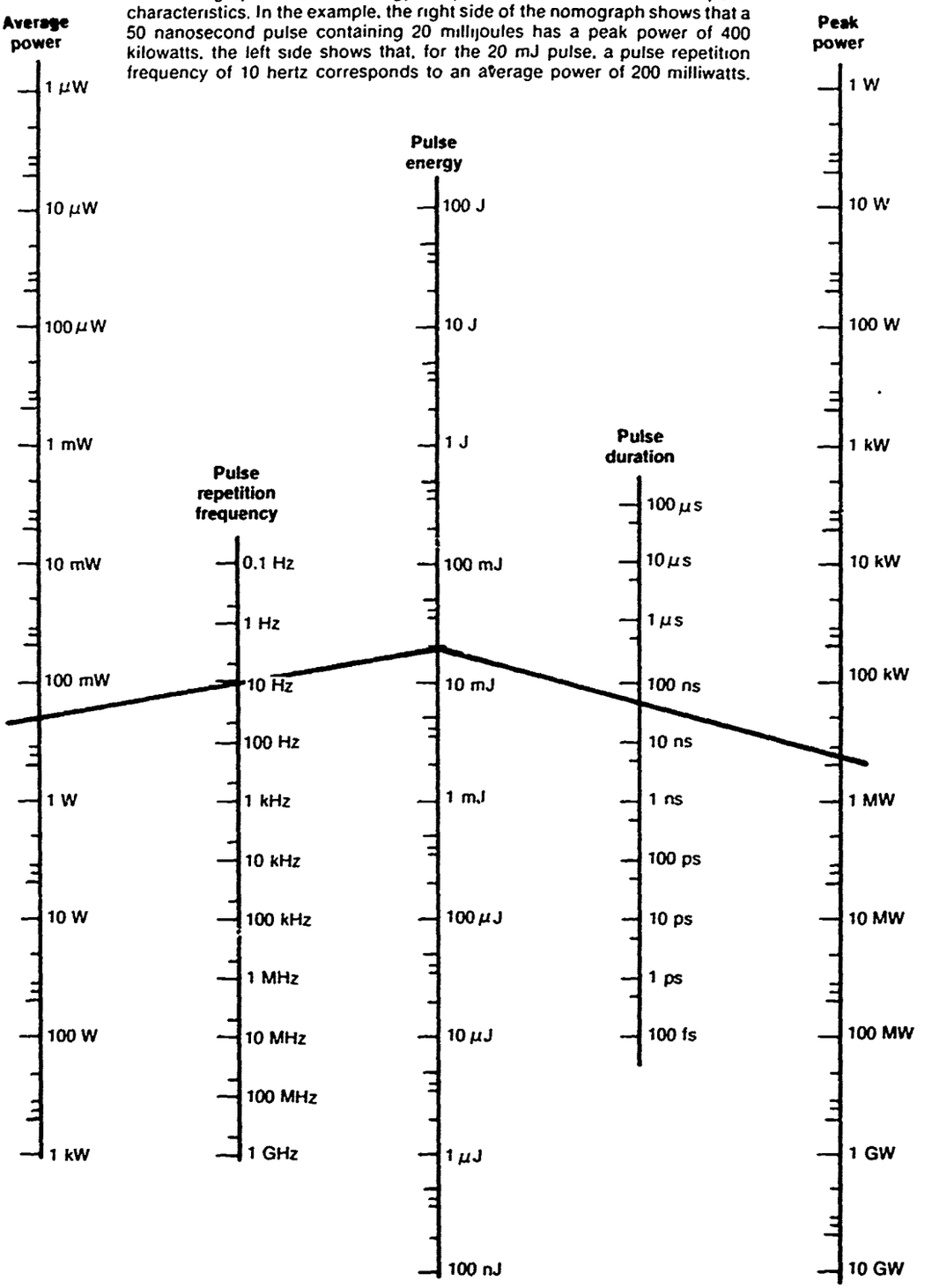


Figure 12.6-9 Pulse energy and power nomograph. (Courtesy of Photonetics Associates; reprinted from 1979 *Laser Focus Buyers' Guide*)

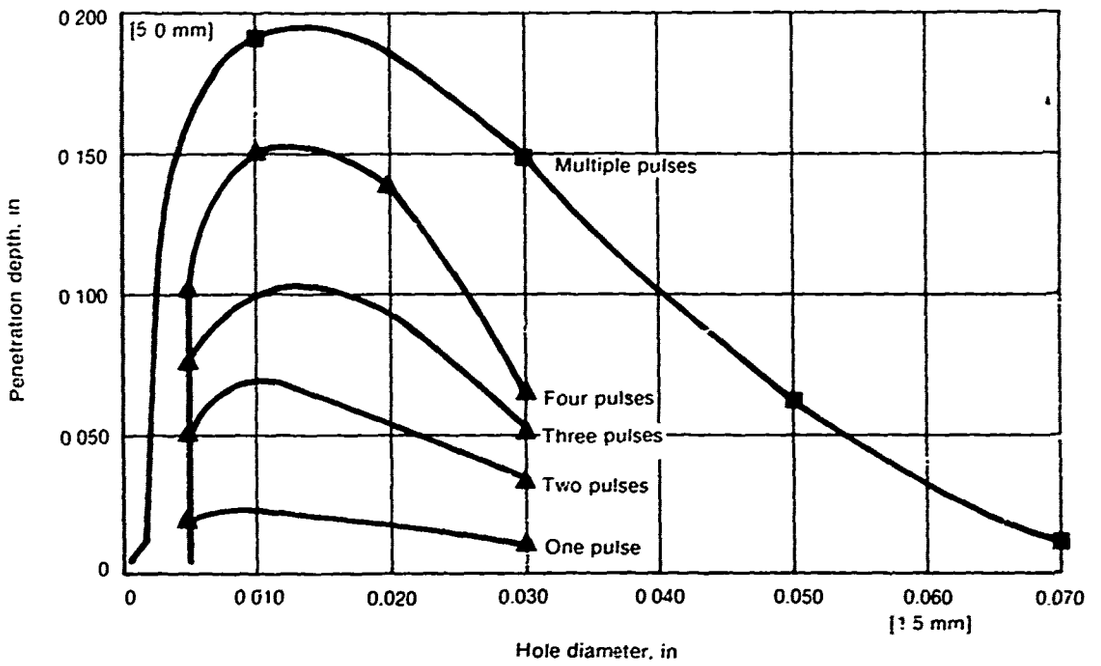


Figure 12.6–10 Capabilities for laser drilling of superalloys.

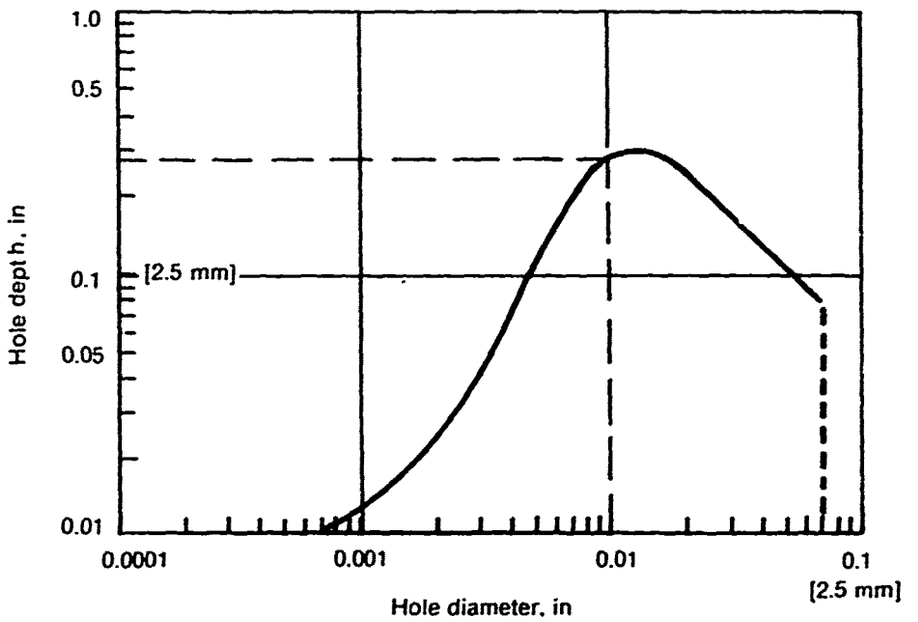


Figure 12.6–11 Typical depth and diameter values for pulsed-laser drilling in ferrous alloys. (Adapted from S. R. Bolin, p. 126.)

12.6 Laser Beam Machining—LBM

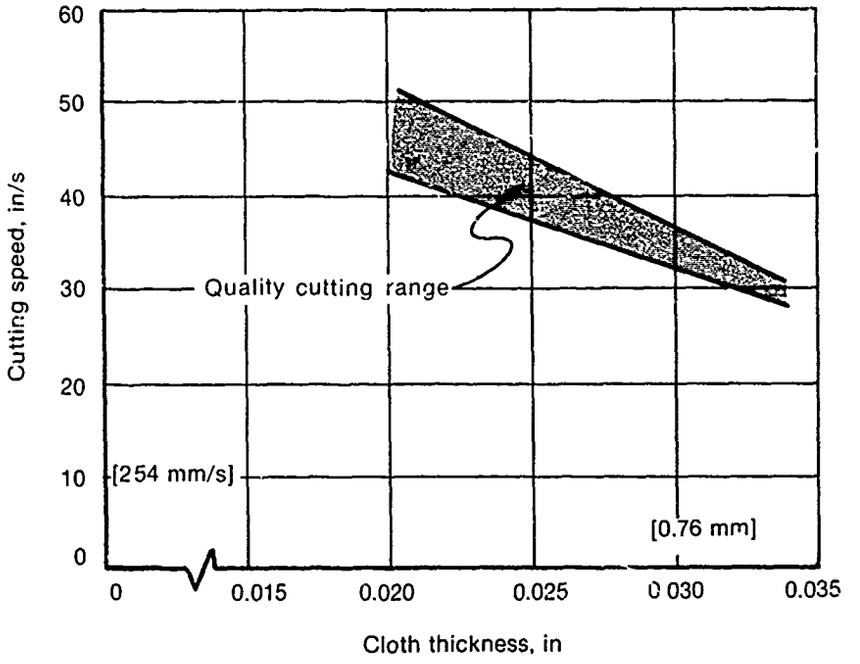


Figure 12.6–12 CO_2-laser cloth cutting (250 watts TEM_{00}). (Courtesy of Coherent, Inc.)

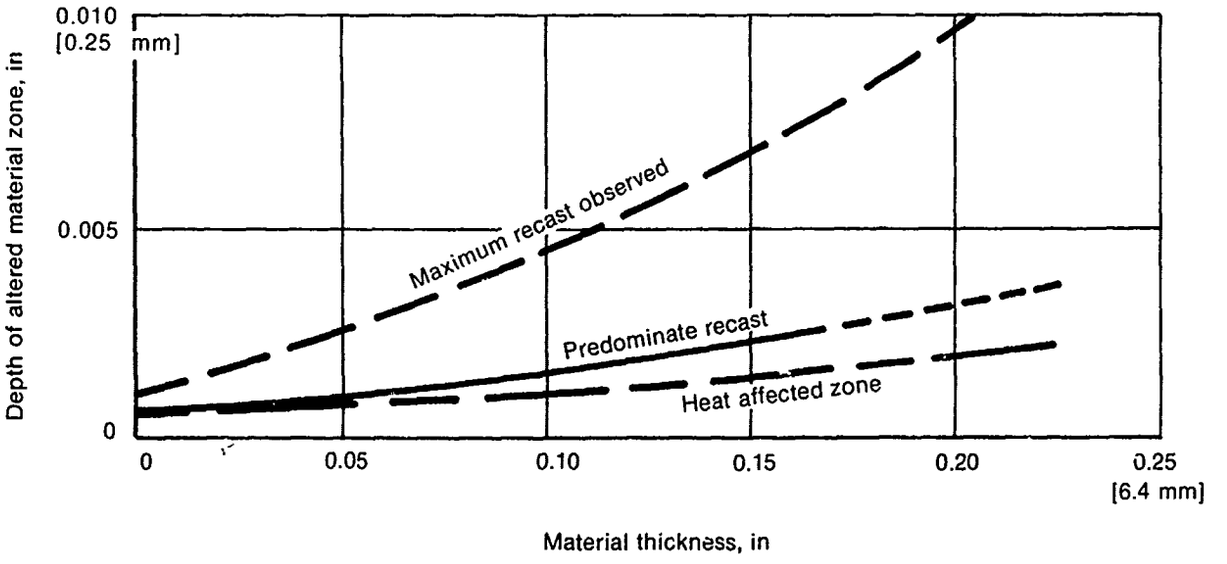


Figure 12.6–13 Surface effects from LBM, circa 1978.

TABLE 12.6-6 CO_2-Laser Drilling of Plastics

MATERIAL	THICKNESS		HOLE DIAMETER				PULSE LENGTH	POWER LEVEL
			Top		Bottom			
	in	mm	in	mm	in	mm	ms	W
PVC	0.025	0.64	0.010	0.25			5.0	50.0
PVC	0.025	0.64	0.030	0.76			40	50
PVC	0.020	0.51	0.012	0.30	0.010	0.25	10	50
PVC			0.023	0.58	0.020	0.51	30	
Acrylic	0.060	1.52	0.007	0.18	0.005	0.13	10	50
Polyethylene	0.006	0.15	0.014	0.36			4.5	150
Polyethylene	0.020	0.51	0.015	0.38			20	50
Polystyrene	0.013	0.33	0 010	0.25			5	50
Polystyrene	0.011	0.28	0.040	1.02			40	50
ABS plastic	0.030	0.76	0.040	1.02			100	50
ABS plastic	0.030	0.76	0.010	0.25			20	50
Mylar	0.0015	0.04	0.005	0.13			0.4	2.6
Acrylic	0.035	0.89	0.016	0.41			10	175
Polycarbonate	0.035	0.89	0.015	0.38			10	175
Nylon	0.035	0.89	0.011	0.28			10.0	175.0

SOURCE: Coherent Inc.

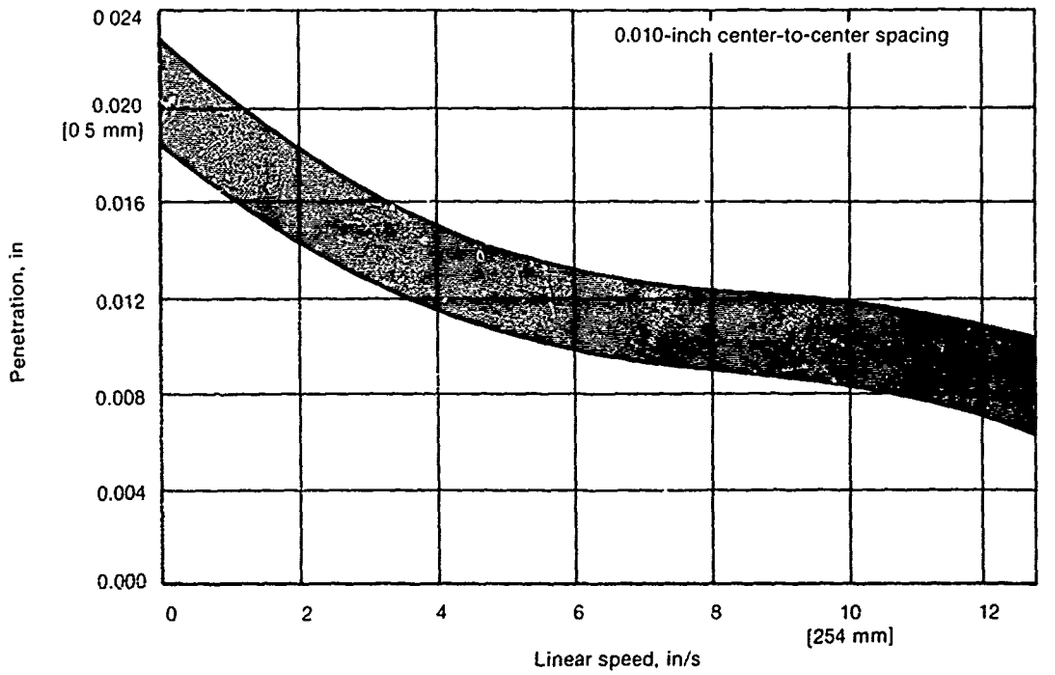


Figure 12.6-14 Ceramic scribing chart—penetration depth versus speed using 185-watt continuous-wave CO_2 laser. Shaded area reflects operating domain expected in production environment with a 1.5-inch focal length lens. (Courtesy of Coherent, Inc.)

12.6 Laser Beam Machining—LBM

SPECIFIC APPLICATIONS DATA

TABLE 12.6–7 Specific Applications Data for Laser Beam Machining

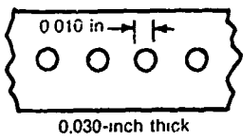
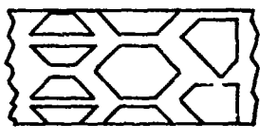
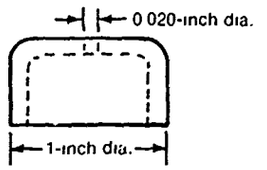
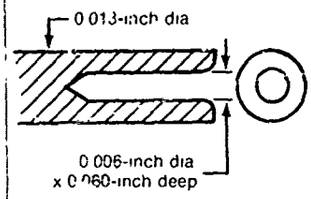
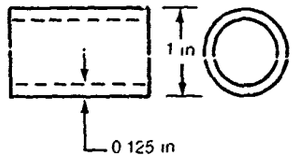
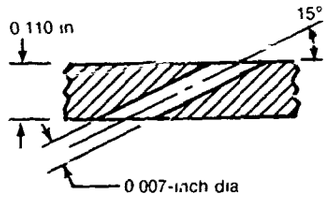
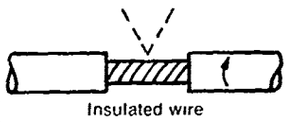
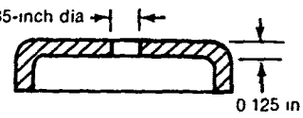
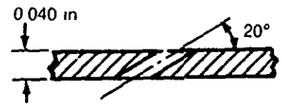
Work material:	**ABS Plastic Strip**	**Cloth, Single Ply**	**Brass Caps**	
Workpiece configuration:				
Laser equipment type:	CO_2	CO_2	Nd-glass	Ruby
wavelength, μm:	10.6	10.6	1.06	0.69
power, W:	250	500		
Operating conditions power level:	50 W			40 J
beam mode:	Pulsed	CW TEM_{00}	Pulsed	Pulsed
pulses per second:			1	1
cycle time:	<1 s	Up to 40 in/s	50 caps/min	
pulse length, ms:	20		0.150	0.60
Tolerance, in:			±0.0003	
Remarks:	Drilled while strip moving. Laser deflection used to reduce relative motion.	Computer controlled nesting and cutting. Seals edge so no fraying.	Vibratory bowl feed for workpieces.	

TABLE 12.6-7—Continued

Work material.	**Stainless Steel Surgical Needle**	**Quartz Tubing, Cutoff**	**Rene 80**
Workpiece configuration.			
Laser equipment type·	Ruby	CO_2	Ruby
wavelength, μm.	0.69	10.6	0.69
power, W.	150 J	500	25 J
Operating conditions power level·	3 J	250 W	14.5 J
beam mode:	Pulsed	CW	Pulsed
pulses per second:	1		1
cycle time:	10 s	4 s	One pulse
pulse length, ms:	1		1
Tolerance, in·			
Remarks.		No cracks and ends smoothed. Room temperature cutting with tube rotating at 60 rpm.	35:1 = length to diameter ratio. 0.002-inch recast.

12.6 Laser Beam Machining—LBM

TABLE 12.6-7—Continued

Work material:	**Kapton Insulated Wire Stripping (No. 26 to 1/0 Wire)**	**Rubber**	**Plastic**
Workpiece configuration:			
Laser equipment type:	CO_2	Ruby	Ruby
wavelength, μm:	10.6	0.69	0.69
power, W:	250	50 J	50 J
Operating conditions power level:	4 W	27 J	25 J
beam mode:	CW	Multi	Multi
pulses per second:		1	1
cycle time:	15 s for #18 wire	30 shots	3 shots
pulse length, ms:		5	6
Tolerance, in:	No action on metal wire.		
Remarks:	Laser beam rotated around wire. Spot size 0.005-inch dia. and 10^5 W/in^2.		

PROCESS SUMMARY

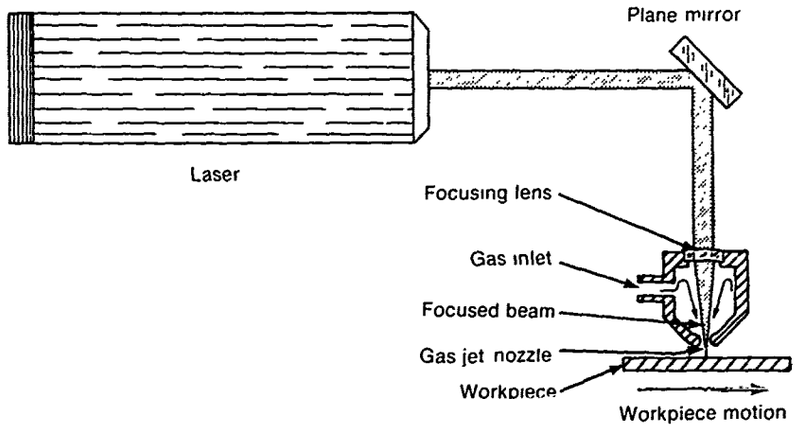


Figure 12.7-1 LBT schematic.

Principles

Laser beam torch (LBT) is a process in which material is removed by the simultaneous focusing of a laser beam and a gas stream on the workpiece (see figure 12.7-1). A continuous-wave (CW) laser or a pulsed laser with more than 100 pulses per second is focused on or slightly below the surface of the workpiece, and the absorbed energy causes localized melting. An oxygen gas stream promotes an exothermic reaction and purges the molten material from the cut. Argon or nitrogen gas is sometimes used to purge the molten material while also protecting the workpiece. Argon or nitrogen gas is often used when organic or ceramic materials are being cut. Close control of the spot size and the focus on the workpiece surface is required for uniform cutting. The type of gas used has only a modest effect on laser penetrating ability (see table 12.7-3 and figure 12.7-19). Typically, short laser pulses with high peak power are used for vaporizing materials (drilling and scribing) while long pulses are used for cutting and welding, as shown in figure 12.7-3. The CO_2 laser is the laser most often used for cutting.

Practical Applications

The LBT cut is characterized by a narrow, tapered kerf and a shallow heat-affected zone. For a given power level, the highest cutting speed yields the best quality of cut and the minimum heat-affected zone. The assisting gas improves the quality and decreases the kerf. Complex contours can be cut in hard materials like silicon carbide, friable materials like glass, or sticky materials like confections. Thin materials are cut at high rates, with 1/8- to 3/8-inch [3.2 to 9.5 mm] thickness a practical limit. Mechanical, optical or numerical control of cuts is usual. Trimming of high strength alloy sheet products with LBT has reduced previous trimming costs as much as 50 percent. Plywood die-board slotting for steel-rule dies, contour-cut titanium plates for aircraft fabrications, stacks of cloth for suits, stripping of wire insulation, and drilling of contact lenses are all practical LBT applications. While most cutting is done on stock less than 0.10-inch [2.5 mm] thick, carbon steel up to 0.50-inch [12.7 mm] thick has been cut at 30 inches per minute [760 mm/min] with higher power lasers. The narrow heat-affected zone minimizes trimming and post-cutting cleanup operations. Before selecting laser as a cutting process, a comparison with other processes is desirable. Table 12.7-4 and figure 12.7-4 contain comparative data. The rapidity of the change in the state of the art of LBT makes it desirable to check with laser builders for the latest process capabilities.

Operating Parameters

See table 12.7-1.

Material Removal Rates and Tolerances

The cutting rates depend upon the thermal properties of the material (table 12.7-5), the material thickness and the power density in the focal spot (figure 12.7-3). A 0.002-inch [0.05 mm] diameter spot can attain a density of 7×10^9 watts per square inch [1.1×10^9 W/mm^2], which is sufficient to vaporize any material. Cutting rates range from 30 inches per minute [750 mm/min] on 1/16-inch [1.6 mm] thick tool steel, to 240 inches per minute [6,100 mm/min] on 0.020-inch [0.5 mm] thick tinplate, to 500 inches per minute [12,700 mm/min] on 0.030-inch [0.75 mm] thick Lexan with a 1/2-kW continuous-wave CO_2 gas laser. This laser will cut 1/4-inch [6.4 mm] thick aluminum at 3 inches per minute [75 mm/min] or 1/4-inch [6.4 mm] thick titanium at 140 inches per minute [3,500 mm/min].

Accuracies up to ± 0.004 inch [± 0.1 mm] are attainable and depend upon the accuracies in the workpiece motion control. Taper is present in most kerfs, as shown in figure 12.7-20, and too high cutting speeds will impart a curved lay pattern in the cut.

12.7 Laser Beam Torch—LBT

TABLE 12.7–1 Typical Values for LBT Operating Parameters

Laser types:	Continuous wave Nd-YAG (cutting) Continuous wave CO_2 (cutting) Q-switch or pulsed ND-YAG (drilling)
Power:	0.25 to 16 kW
Gas	
types:	Oxygen, nitrogen, argon, air, helium
pressure:	20 to 120 psi [140 to 825 kPa]
nozzle diameter:	0.020 to 0.040 inch [0.5 to 1 mm]
nozzle gap:	0.020 ±0.010 inch [0.5 ±0.25 mm]
Focus	
spot size:	0.002 inch [0.05 mm] smallest diameter 0.003 to 0.010 inch [0.07 to 0.25 mm] usual
depth of focus*:	0.030 to 0.33 inch [0.76 to 8.4 mm]
focal length:	1.5 to 5 inches [40 to 130 mm]
focal point:	Surface or slightly below
Trim/cleanup setback:	0.5 to 3 times stock thickness
Kerf:	0.004 to 0.080 inch [0.1 to 2 mm] (see table 12.7–7 and figures 12.7–20 to 12.7–24)
Heat-affected zone (HAZ):	0.001 to 0.010 inch [0.025 to 0.25 mm]
Cutting rates (feed rate):	10 to 300 in/min [250 to 7,500 mm/min] (see table 12.7–7 and figures 12.7–6 to 12.7- 19)
Cut thickness capability for	
nonferrous alloys:	Up to 0.040 inch [1 mm]
ferrous and titanium alloys:	Up to 0.200 inch [5 mm]
nonmetals:	Up to 0.10 inch [2.5 mm]
nickel alloys:	Up to 0.60 inch [1.5 mm]
plastics:	Up to 0.20 inch [5 mm]
Minimum outside trim radius:	0.50 inch [12.7 mm]

*Distance between which spot size is no more than 40 percent larger than at focus.

Surface Technology

A heat-affected zone (HAZ) is present in all laser cuts but the rapidity of the metal removal can leave less HAZ than competing processes (see table 12.7–7 and LBM section, figure 12.6–13). Surface roughness is high—125 to 250 microinches R_a [3.2 to 6.3 μm] being typical. The amount of stock removal needed to clean up the roughness or HAZ is minimal and ranges from one-fourth to three times the stock thickness. Dross attached to the underside of the cut usually is easy to remove.

Equipment and Tools

LBT equipment is available in 1/4- to 16-kW sizes in worktable sizes up to 4 by 6 feet [1.3 by 2 m]. NC, optically or mechanically guided torches or workpieces are available to cut straight or intricate contours. Multiple torch combinations and LBT combined with punch presses have been built. Laser cutting forces are almost nonexistent so fixturing is less complicated. Rotating mechanisms for the lens (or mirrors) are employed when trepanning larger-size holes.

Machining Characteristics

It is essential to keep the laser beam focused accurately on the workpiece. Optical and mechanical contour followers are available to adjust the torch focus when working on sheets with undulations. Adequate fume and sight protection are needed for LBT.

The noncontacting tool in LBT increases tool life almost indefinitely. The choice of gas used can be influenced by the need for protection of the workpiece material (see table 12.7–6).

SELECTED DATA

There are several valid techniques for selecting operating parameters for LBT. The steps in table 12.7-2 are recommended as one logical sequence. Supporting data come from the other figures and tables in accordance with the terms as explained in figure 12.7-2.

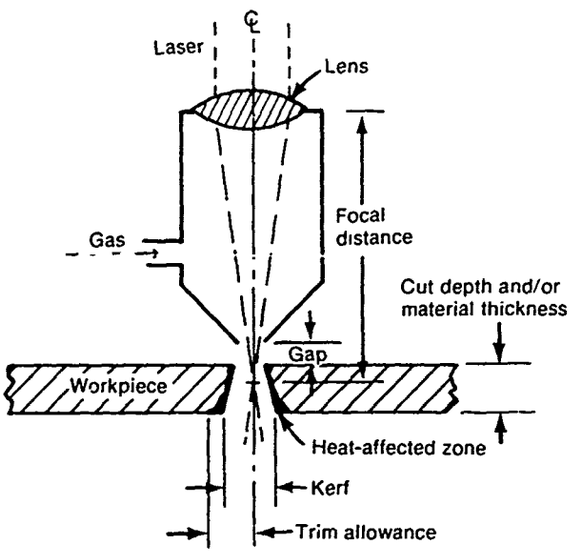


Figure 12.7-2 LBT parameter terminology.

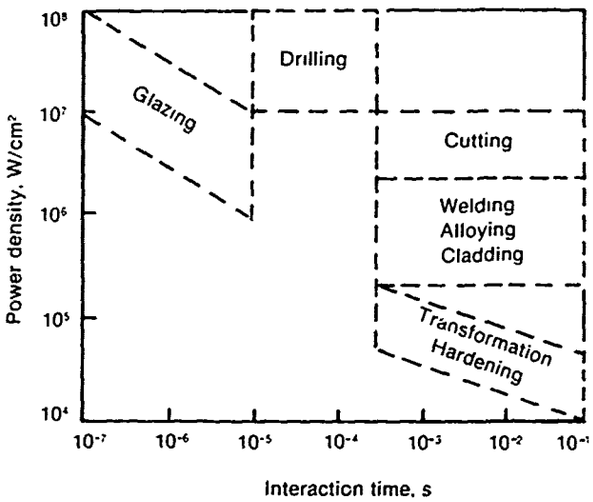


Figure 12.7-3 Laser material processing applications in terms of power density and interaction time. (A. Schachrai and M. Castellani-Longo, Application of high power lasers in manufacturing, *Annals of the CIRP*, Vol. 28/2, 1979, p. 466)

TABLE 12.7-2 Steps to Select LBT Operating Parameters

ITEM	DATA
1. Workpiece material characteristics	Engineering drawing and table 12.7-5
2. Applicability of LBT	Comparison of saw, nibble, plasma-arc, oxyacetylene, etc., with laser, table 12.7-4 and figures 12.7-3 and 12.7-4
3. Select assisting gas	Tables 12.7-3 and 12.7-6 and figure 12.7-19
4. Material thickness (cut depth)	Engineering drawing
5. Select power level and cutting rate	Figures 12.7-5 to 12.7-25 Table 12.7-7
6. Estimate kerf and heat-affected zone (HAZ)	Table 12.7-7 and figures 12.7-20 to 12.7-25
7. Template design with trim allowance	Figure 12.7-20 and item 6
8. Cutting gap setting	Trial cut to verify parameters and edge finish

TABLE 12.7-3 Penetration of CO_2 Laser in Perspex (Boxboard) with Various Gases

GAS	PENETRATION	
	in	mm
Helium	0.93	[illegible]
Nitrogen	0.94	[illegible]
Oxygen	0.89	[illegible]
Air	0.96	[illegible]
Argon	1.00	[illegible]
Carbon dioxide	0.87	[illegible]
Argon/hydrogen, 75/25	0.91	[illegible]

SOURCE: F. W. Lunau, Boc-Murex Welding Research and Development Laboratories, London.

12.7 Laser Beam Torch—LBT

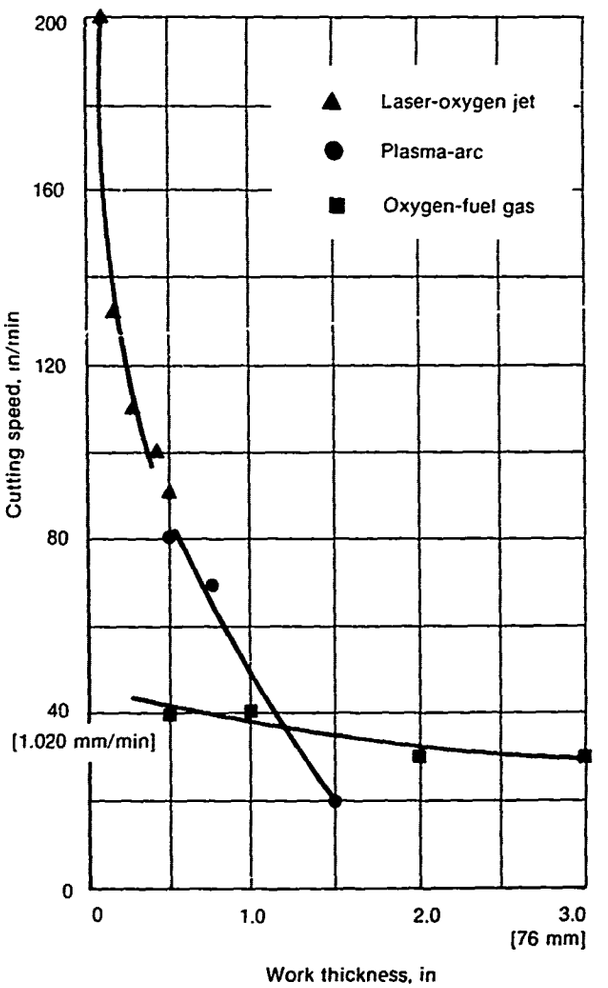


Figure 12.7–4 Comparative cutting speeds of laser beam torch, plasma-arc torch and oxyacetylene torch for titanium alloys. (Courtesy of I. Slater, The Boeing Company)

TABLE 12.7–4 Comparison of Cutting Rates Among Competing Processes

MATERIAL	TYPE OF CUT	WORK THICKNESS		PUNCH PRESS NIBBLER		BAND SAW		OXYACETYLENE TORCH		PLASMA-ARC TORCH		LASER TORCH CW-CO_2 at 250 W plus O_2 gas assist	
				Cutting Speed									
		in	mm	in/min	m/min	in/min	m/min	in/min	m/min	in/min	m/min	in/min	m/min
Titanium alloy	Contour	0.020	0.5			8.5	0.22					200	5
	Contour	0.062	1.5			5.8	0.15					160	4
	Contour	0.125	3	20	0.5	4.4	0.11	60	1.5	60	1.5	120	3
	Straight	0.250	6			23	0.58	100	2.54	167	4.2	200	5.1
	Contour	0.250	6			3	0.08	30	0.75	50	1.25	60	1.5
	Contour	0.50	12			1	0.03	20	0.5	35	0.9	40	1
	Contour	1	25					15	0.4	30	0.75	15*	0.4
	Contour	2	50					16	0.4	22	0.6	5*	0.13
Steel	Contour	0.020	0.5			8.5	0.22					80	2
	Contour	0.062	1.5			5.8	0.15					40	1
	Contour	0.125	3			4.4	0.11					20	0.5
4130 Alloy steel	Contour	0.100	2.5	30	0.75	20	0.5	30	0.75	30	0.75	65	1.7
4340 Alloy steel	Contour	0.375	8.6			14	0.36	80	2.0	88	2.2	35*	0.9
	Contour	0.75	17			10	0.25	50	1.3	60	1.5	15*	0.4
Stainless steel	Contour	0.050	1.3	30	0.75	25	0.6	10	0.25	10	0.25	18	0.46

* 16 kw laser

TABLE 12.7–5 Properties of Metals and Alloys Important for Oxygen-Laser Cutting

MATERIAL	ELECTRICAL RESISTIVITY at 68°F ohm-cm	THERMAL CONDUCTIVITY at 212°F BTU/hr/ft²/ft/°F	THERMAL DIFFUSIVITY ft²/hr	OXIDE	OXIDE MELTING POINT °F	HEAT OF COMBUSTION kcal/cm³metal
Ti-6Al-4V	176	4.3	0.12	TiO_2	3,360	12.9
Titanium	55	9.8	0.29	TiO_2	3,360	12.9
4340 Alloy steel		22	0.43	Fe_2O_3	2,840	14.1
C1020 Carbon steel	14.3	27	0.52	Fe_2O_3	2,840	14.1
Zircaloy-2	74	8.1	0.29	ZrO_2	4,930	16.3
321 Stainless steel	72	9.3	0.13	Cr_2O_4	4,130	14.4
6061 Aluminum alloy	3.8	99	2.5	Al_2O_3	3,720	20.2
Copper ETP	1.71	226	4.4	Cu_2O	2,260	2.8

TABLE 12.7–6 Gas Selection for LBT

MATERIAL CLASS	BEST	OPTIONAL
Steels	Air	O_2, N_2
Titanium	Helium	Helium/argon, CO_2
Nonferrous alloys	O_2	Air
Nickel alloys	O_2	Air, O_2
Nonmetals	O_2	Air
Composites	O_2	N_2, argon
Plastics	O_2	Air, argon
Wood products	N_2	Air, O_2

TABLE 12.7–7 Feed Rates for CO_2 Laser Beam Torch

MATERIAL	THICKNESS		CUTTING RATE		POWER	ASSISTING GAS			KERF WIDTH				HEAT-AFFECTED ZONE	
						Type	Pressure		Inlet		Outlet			
	in	mm	in/min	mm/min	watts		psi	kPa	in	mm	in	mm	in	mm
STEELS														
Mild steel	0.039	1.0	118	3,000	230*	O_2					0.004	0.1		
	0.039	1.0	177	4,500	400	O_2								
	0.051	1.3	142	3,610	500	air								
	0.063	1.6	98	2,500	500	air								
	0.09	2.3	70	1,780	650	O_2								
	0.118	3.0	60	1,520	350	O_2								
	0.119	3.0	24	610	230*	O_2					0.008	0.2		
	0.126	3.2	40	1,020	500	O_2								
C1010	0.125	3.2	22	560	190	O_2			0.04	1.0				
Low carbon	0.125	3.2	100	2,540	4,000	air								
Mild steel	0.252	6.4	20	510	500	O_2								
Low carbon	0.66	16.8	45	1,140	4,000	air								
Stainless steel	0.004	0.1	197	5,000	500	O_2								
	0.012	0.3	146	3,710	500	O_2								
321	0.02	0.5	92	2,340	165	O_2			0.012	0.3				
	0.02	0.5	750	19,000	1,000	O_2								
17-7 PH, 321	0.025	0.6	180	4,570	250	O_2								
	0.032	0.8	650	16,500	1,000	O_2								
	0.039	1.0	65	1,650	500	O_2								
321	0.04	1.0	550	14,000	1,000	O_2								
	0.05	1.3	30	760	165	O_2			0.02	0.5				
	0.059	1.5	18	460	400	O_2								
	0.062	1.6	450	11,400	1,000	O_2								
	0.063	1.6	75	1,900	500	O_2								
321,410,17-7 PH	0.063	1.6	60	1,520	250	O_2	60	414						
	0.08	2.0	325	8,260	1,000	O_2								
17-7 PH, 321	0.09	2.3	30	760	250	O_2								
	0.11	2.5	47	1,190	400	O_2								
	0.118	3.0	45	1,140	400	O_2								
321,410,17-7 PH	0.125	3.2	10	250	250	O_2	70	483						
300 or 400 series	0.125	3.2	100	2,540	3,000	air								
	0.125	3.2	200	5,080	1,000	O_2								
	0.126	3.2	35	890	500	O_2								
	0.252	6.4	20	510	500	O_2								

NOTE: Cutting rates are not necessarily maximum for any given thickness. The rates consider other parameters for acceptable cuts, such as kerf width, gas consumption, depth of heat-affected zone (HAZ), etc.

*TEM 0 1

TABLE 12.7–7—Continued

MATERIAL	THICKNESS		CUTTING RATE		POWER	ASSISTING GAS			KERF WIDTH				HEAT-AFFECTED ZONE	
						Type	Pressure		Inlet		Outlet			
	in	mm	in/min	mm/min	watts		psi	kPa	in	mm	in	mm	in	mm
Galvanized steel	0.02	0.5	250	6,350	1,000	O_2								
	0.03	0.75	137	3,480	230*	O_2					0.004	0.1		
	0.039	1.0		4,500	400	O_2								
	0.04	1.0	100	2,540	1,000	O_2								
	0.051	1.3	142	3,610	400	O_2								
	0.062	1.6	50	1,270	1,000	O_2								
	0.118	3.0	60	1,520	400	O_2								
Tinplate steel	0.02	0.5	240	6,100	500	O_2								
High speed steel	0.093	2.4	35	890	500	O_2								
HI C steel	0.118	3.0	59	1,500	400	O_2								
High speed steel	0.134	3.4	24	610	500	O_2								
	0.165	4.2	16	410	500	O_2								
	0.205	5.2	27	690	500	O_2								
	0.22	5.6	23	580	500	O_2								
	0.28	7.1	3	75	500	O_2								
Low alloy steel	0.024	0.6	23	580	850	O_2								
Maraging steel	0.189	4.8	3	75	500	O_2								
H25 tool steel	0.063	1.6	31	790	500	O_2								
Martensitic stainless steel	0.2	5.1	30	760	550	O_2								
	0.31	7.9	15	380	650	O_2								
18-8 austenitic stainless steel	0.039	1.0	59	1,500	230*	O_2					0.004	0.1		
	0.125	3.2	30	760										
Nimonic														
90	0.039	1.0	96	2,440	500	O_2								
80	0.059	1.5	23	580	250	O_2								
90	0.059	1.5	90	2,290	850	O_2								
75	0.002	0.05	98	2,490	500	O_2								
80A	0.028	0.7	180	4,570	650	O_2								
70	0.028	0.7	80	2,030	650	O_2								
75	0.047	1.2	51	1,300	500	O_2								
90	0.05	1.3	90	2,290	650	O_2								
75	0.079	2.0	31	790	500	O_2								
4340 steel	0.025	0.6	120	3,050	250	O_2	40	280						
	0.063	1.6	65	1,650	250	O_2	50†	340†						
	0.09	2.3	60	1,520	250	O_2	40	280						

*TEM 0.1. †Nozzle diameter = 0.035 inch (0.9 mm).

TABLE 12.7-7—Continued

MATERIAL	THICKNESS		CUTTING RATE		POWER	ASSISTING GAS			KERF WIDTH				HEAT-AFFECTED ZONE	
						Type	Pressure		Inlet		Outlet			
	in	mm	in/min	mm/min	watts		psi	kPa	in	mm	in	mm	in	mm
4340 steel (cont.)	0.125	3.2	30	760	250	O_2	60[1]	410						
	0.125	3.2	50	1,270	750	O_2	75	520	0.032	0.81	0.052	1.32	0.013	0.33
	0.125	3.2	70	1,780	1,500	O_2	120	830	0.035	0.89	0.041	1.04	0.011	0.28
	0.125	3.2	130	3,300	3,000	O_2	120	830	0.027	0.69	0.042	1.07	0.025	0.64
	0.125	3.2	200	5,080	6,000	O_2	200	1,380	0.021	0.53	0.024	0.61	0.014	0.36
	0.125	3.2	45	1,140	1,500	O_2	200	1,380	0.04	1.02	0.043	1.09	0.012	0.30
	0.125	3.2	50	1,270	1,500	CO_2	100	690	0.016	0.41	0.014	0.36	0.025	0.64
	0.125	3.2	80	2,030	3,000	CO_2	120	830	0.013	0.33	0.015	0.38	0.026	0.66
	0.125	3.2	100	2,540	6,000	CO_2	250	1,720	0.02	0.51	0.016	0.41	0.032	0.81
	0.125	3.2	80	2,030	3,000	N_2	200	1,380	0.02	0.51	0.022	0.56	0.014	0.36
	0.125	3.2	80	2,030	3,000	air	200	1,380	0.024	0.61	0.014	0.36	0.021	0.53
	0.25	6.4	70	1,780	3,000	O_2	150	1,030	0.047	1.19	0.058	1.47	0.014	0.36
	0.25	6.4	100	2,540	6,000	O_2	180	1,240	0.061	1.55	0.063	1.60	0.045	1.14
	0.25	6.4	15	380	3,000	CO_2	200	1,380	0.021	0.53	0.03	0.76	0.033	0.84
	0.25	6.4	30	760	6,000	CO_2	200	1,380	0.025	0.64	0.025	0.64	0.033	0.84
	0.38	9.7	30	760	3,000	O_2	200	1,380	0.055	1.40	0.129	3.27	0.038	0.97
	0.38	9.7	60	1,520	6,000	O_2	200	1,380	0.054	1.37	0.125	3.18		
	0.38	9.7	18	460	6,000	CO_2	350	2,410	0.025	0.64	0.014	0.36	0.057	1.45
	0.75	19.1	45	1,140	10,000	O_2								
	0.75	19.1	9.4	240	10,000	air								
	0.75	19.1	10	250	10,000	He			0.09	2.29	0.054	1.37	0.099	2.51
	0.75	19.1	15	380	15,000	75%He, 25%A								
	0.75	19.1	15	380	15,000	He			0.09	2.29	0.037	0.94	0.097	2.46
NONFERROUS														
Aluminum	0.02	0.5	800	20,300	1,000	O_2								
	0.04	1.0	350	8,900	1,000	O_2								
	0.062	1.6	200	5,080	1,000	O_2								
	0.125	3.2	100	2,540	1,000	O_2								
	0.24	6.1	1.2	30	3,800	O_2								
	0.25	6.4	40	1,020	3,800	air								
	0.5	12.7	40	1,020	10,000	O_2								
	0.5	12.7	90	2,290	15,000	O_2								
	0.5	12.7	30	760	5,700	air								
Brass	0.005	0.1	156	3,960	275	O_2								
Copper (dag coated)	0.008	0.2	23	580	500	O_2								
Niobium	0.126	3.2	8	200	500	O_2								

[1]Nozzle diameter = 0.035 inch (0.9 mm).

TABLE 12.7-7—Continued

MATERIAL	THICKNESS		CUTTING RATE		POWER	ASSISTING GAS			KERF WIDTH				HEAT-AFFECTED ZONE	
						Type	Pressure		Inlet		Outlet			
	in	mm	in/min	mm/min	watts		psi	MPa	in	mm	in	mm	in	mm
Molybdenum	0.002		16		500	O_2								
Zircaloy	0.018		600		230	O_2								
Titanium, CP	0.02		600		135	O_2			0.02	0.51				
Ti-6Al-4V or Ti-6Al-6V-2Sn	0.025		300		250	O_2	40		0.015	0.38				
	0.05		300		210	O_2	50							
	0.062		120		3,000	N	200		0.03	0.76				
									0.016	0.41	0.015	0.38	0.008	0.2
	0.062		120		3,000	air	200		0.036	0.91	0.03	0.76	0.021	0.53
	0.08		708		230°	O_2						0.008	0.2	
	0.09		108		210	O_2	40		0.03	0.76				
	0.118		161		400	air								
	0.125		200		250	O_2	40							
	0.125		60		1,500	CO_2	200		0.019	0.48	0.02	0.51		
	0.125		80		3,000	air	200		0.023	0.58	0.02	0.51	0.04	1
	0.125		80		3,000	N	200		0.022	0.56	0.022	0.56	0.023	0.58
	0.125		70		3,000	N	20		0.012	0.3	0.012	0.3	0.018	0.46
	0.18		170		250	O_2	40							
	0.200		130		650	O_2								
	0.212		160		250	O_2	80							
	0.25		80		250	O_2	40		0.040	1.02	0.035	0.89	0.005	0.13
	0.25		108		250	O_2			0.061[1]	1.55[1]	0.019[1]	0.48[1]	0.040	1.02
	0.25		80		10,000	He								
	0.25		140		3,000	air								
	0.25		60		750	O_2	60		0.060	1.52	0.075	1.91	0.019	0.48
	0.25		100		1,500	O_2	60		0.055	1.40	0.070	1.78	0.017	0.43
	0.25		140		3,000	O_2	80		0.060	1.52	0.070	1.78	0.016	0.41
	0.25		180		6,000	O_2	150		0.102	2.59	0.092	2.34	0.037	0.94
	0.25		14		3,000	CO_2	300		0.022	0.56	0.032	0.81	0.061	1.55
	0.25		60		6,000	CO_2	300		0.030	0.76	0.019	0.48	0.056	1.42
	0.25		142		500	O_2								
	0.35		60		250	O_2	50							
	0.39		100		260	O_2			0.065	1.65			0.005	0.13
	0.39		110		230°	O_2					0.060	1.52		
	0.40		60		250	O_2			0.035	0.89	0.063	1.60		
	0.50		40		250	O_2	70							
	0.75		50		1,500	O_2	100		0.062	1.57	0.123	3.12	0.054	1.37
	0.75		60		3,000	O_2	120		0.058	1.47	0.136	3.45	0.039	0.99

[1]TEM 0.1. [2]Smoother cut.

TABLE 12.7-7—Continued

MATERIAL	THICKNESS		CUTTING RATE		POWER	ASSISTING GAS		KERF WIDTH				HEAT-AFFECTED ZONE	
						Type	Pressure	Inlet		Outlet			
	in	mm	in/min	mm/min	watts		psi kPa	in	mm	in	mm	in	mm
Ti-6Al-4V or Ti-6Al-6V-2Sn (cont.)	0.75	19.1	80	2,030	6,000	O_2	140 970	0.094	2.39	0.162	4.11	0.017	0.43
	0.75	19.1	15	380	10,000	He		0.067	1.70	0.036	0.91	0.105	2.67
	0.75	19.1	100	2,540	10,000	O_2							
	0.80	20.3	100	2,540	11,000	O_2							
	1.00	25.4	20	510	230*	O_2				0.137	3.48		
	1.00	25.4	60	1,520	3,000	O_2	150 1,030	0.085	2.16	0.190	4.83	0.046	1.17
	1.00	25.4	15	380	15,000	He		0.093	2.36	0.046†	1.17†	0.09	2.29
	1.25	31.8	50	1,270	3,000	O_2							
	2.00	50.8	20	510	3,000	O_2							
	2.00	50.8	40	1,020	6,000	O_2	200 1,380	0.118	3.00	0.5‡	12.7‡		
	2.00	50.8	5	130	15,000	He						0.165	4.19
Titanium honeycomb	0.25	6.4	100	2,540	3,000	O_2							
NICKEL ALLOYS													
Haynes alloy 188	0.02	0.5	90	2,300	250	O_2	50 340						
	0.063	1.6	10	250	250	O_2	50 340						
TD-Ni Cr	0.015	0.4	20	510	250	O_2	70 480						
	0.060	1.5	10	250	250	O_2	60 410						
MN-nickel alloy	0.003	0.1	67	1,700	500	O_2							
Inconel alloy 718	0.500	12.7	50	1,270	11,000	O_2							
Monel mesh	2.000	50.8	4	100	500	O_2							
Nickel-tungsten	0.002	0.05	31	790	500	O_2							
Waspaloy	0.03	0.8	400	10,200	750	O_2	100 690	0.01	0.25	0.01	0.25	0.005	0.13
	0.03	0.8	400	10,200	1,500	O_2	100 690	0.01	0.25	0.008	0.20	0.004	0.10
	0.03	0.8	600	15,200	3,000	O_2	100 690					0.002	0.05
	0.03	0.8	720	18,300	6,000	O_2	175 1,210	0.022	0.56	0.018	0.46	0.002	0.05
	0.03	0.8	140	3,560	750	CO_2	100 690	0.012	0.30	0.008	0.20	0.001	0.03
	0.03	0.8	280	7,110	1,500	CO_2	100 690	0.007	0.20	0.006	0.15	0.001	0.03
	0.03	0.8	500	12,700	3,000	CO_2	200 1,380	0.014	0.36	0.013	0.33	0.002	0.05
	0.03	0.8	650	16,500	6,000	CO_2	250 1,720	0.016	0.41	0.015	0.38	<0.001	<0.03
	0 06	1.5	100	2,540	750	O_2	100 690	0.011	0.28	0.011	0.28	0.005	0.13
	0.06	1.5	240	6,100	1,500	O_2	200 1,380	0.010	0.25	0.010	0.25	0.003	0.08
	0.06	1.5	350	8,900	3,000	O_2	100 690	0.018	0.46	0.018	0.46	0.004	0.10
	0.06	1.5	450	11,400	6,000	O_2	150 1,030	0.017	0.43	0.030	0.76	0.045	1.14

*TEM 0.1. †Smoother cut.

TABLE 12.7–7—Continued

MATERIAL	THICKNESS		CUTTING RATE		POWER	ASSISTING GAS			KERF WIDTH				HEAT-AFFECTED ZONE	
						Type	Pressure		Inlet		Outlet			
	in	mm	in/min	mm/min	watts		psi	kPa	in	mm	in	mm	in	mm
Waspaloy (cont.)	0.06	1.5	200	5,080	3,000	CO_2	200	1,380	0 015	0.38	0.005	0.13	0.002	0.05
	0.06	1.5	350	8,900	6,000	CO_2	200	1,380	0.023	0.58	0 022	0.56	0.003	0.08
	0.125	3.2	50	1,270	750	O_2	200	1,380	0 011	0.28	0.013	0.33	0.004	0.10
	0.125	3.2	80	2,030	1,500	O_2	100	690	0.001	0.03	0 012	0.30	0 006	0.15
	0.125	3.2	140	3,560	3,000	O_2	120	830	0.019	0.48	0 023	0.58	0.006	0.15
	0.125	3.2	270	6,860	6,000	O_2	150	1,030	0 017	0.43	0.030	0.76	0 003	0.08
	0.125	3.2	140	3,560	6,000	CO_2	300	2,070	0.020	0.51	0.019	0.48	0.003	0.08
Nickel	0.005	0.1	156	3,960	275	O_2								
Rene 41	0.02	0.5	80	2,030	250	O_2	40	280						
	0.05	1.3	20	510	250	O_2	40	280						
	0.063	1.6	15	380	250	O_2	40	280						
Hastelloy alloy X	0.02	0.5	70	1,780	250	O_2	40	280						
	0.02	0.5	52	1,320	165	O_2								
	0.05	1.3	30	760	250	O_2	40	280						
NONMETALS														
Alumina	0.024	0.6	90	2,290	500	O_2								
	0.025	0.6	50	1,270	250	N_2			0 012	0.3				
	0.039	1.0	118	3,000	230*	O_2					0.004	0.1		
Asbestos cement	0.150	3.8	0.6	15	200	air								
Carborundum	0.040	1.0	19	480	200	air								
Ceramic	0.025	0.6	500	12,700	1,000	O_2								
Ceramic tile	0.250	6.4	19	480	850	O_2								
Glass	0.010	0.3	42	1,070	400	O_2								
Quartz	0.125	3.2	29	740	500	O_2								
Quartz glass	0.075	1.9	24	610	230*	O_2					0.008	0.2		
Silica	0.040	1.0	94	2,390	500	O_2								
Soda glass	0.005	0.1	125.0	3,180	200	air								
	0.040	1.0	9.5	240	200	air								
	0.100	2.5	2 5	64	200	air								
Tungsten carbide	0.071	1.8	1.8	46	500	O_2								
	0.189	4.8	1.8	46	500	O_2								

*TEM 0.1.

TABLE 12.7–7—Continued

MATERIAL	THICKNESS		CUTTING RATE		POWER	ASSISTING GAS			KERF WIDTH				HEAT-AFFECTED ZONE	
						Type	Pressure		Inlet		Outlet			
	in	mm	in/min	mm/min	watts		psi	kPa	in	mm	in	mm	in	mm
ORGANICS, PLASTICS, ETC.														
ABS Plastic	0.035	0.9	324	8,230	250	air	60	413			0.025[a]	0.64[a]		
	0 042	1.1	258	6,550	250	air	60	413			0.025	0.64		
	0.075	1.9	90	2,290	250	air	60	413			0.030	0.76		
	0.095	2.4	120	3,050	250	air	60	413			[a]	[a]		
	0.100	2.5	150	3,810	240	N_2			0.030	0.76				
(extruded)	0.100	2.5	120	3,050	250	air	60	413			0.025	0.64		
	0.160	4.1	160	4,060	240	O_2								
Carpet, polyester	0.250	6.4	120	3,060	200	A			0.020	0.51				
	0.375	9.5	120	3,050	200	A			0 020	0.51				
	0.390	9.9	102	2,590	230[a]	N_2					0.020	0.51		
Carpet, needle cord	0.220	5.6	320	8,130	230*	N_2					0.012	0.30		
Cotton fabric, multilayer	0.710	18.0	8	200	230*	N_2					0.027	0.69		
Delrin	0.026	0.7	588	14,900	380	O_2								
Fiberglass reinforced plastic	0 130	3.3	24	610	230*	N_2					0.012	0.30		
Hardboard	0.125	3.2	270	6,860	650	O_2								
	0.200	5.1	180	4,570	650	O_2								
Leather	0.080	2.0	16	410	200	air								
Lexan	0.030	0.8	498	12,650	380	O_2								
Mylar film	0.001	0.02	48,000	1.22 km	300	O_2								
Nylon	0.020	0.51	125	3,180	200	air								
PVC Sheet	0.0012	0.03	3,000	76,200	300	O_2								
	0.012	0.3	118	3,000	100	O_2								
	0.280	7.1	47	1,200	230	N_2					C.02	0 51		
	0.393	10.0	189	4,800	340	O_2								
Packageboard (Perspex)	0.086	2.2	16	410	200	air								
	0.250	6.4	5	130	200	air								
	0.625	15.8	2.5	65	200	air								
	1.250	31.7	12	300	650	O_2								
Perspex, embossed	0.120	3.0	177	4,500	230*	N_2					0.015	0.38		
Perspex, transparent	0.390	10.0	32	810	230*	N_2					0 027	0.69		

*TEM 0.1. [a]Smooth, clean cut.

TABLE 12.7–7—Continued

MATERIAL	THICKNESS		CUTTING RATE		POWER	ASSISTING GAS			KERF WIDTH				HEAT-AFFECTED ZONE	
						Type	Pressure		Inlet		Outlet			
	in	mm	in/min	mm/min	watts		psi	kPa	in	mm	in	mm	in	mm
Plexiglas	0.125	3.2	150	3,810	250	O_2	40	275						
Polycarbonate	0.250	6.4	15	380	250	air	60	413			0.04#	1.02#		
Polyethylene	0.060	1.5	78	1,980	250	air	60	413			**	**		
	0.090	2.3	48	1,220	250	air	60	413			**	**		
	0.115	2.9	39	990	250	air	60	413			**	**		
Polypropane	0.500	12.7	9.6	240	250	air	60	413			0.055††	1.4††		
Polypropylene	0.012	0.3	540	13,700	50	air	20	138			0.008††	0.20††		
	0.220	5.6	27	690	230*	N_2					0.020	0.51		
	0.045	1.1	180	4,570	250	air	60	413			††	††		
Polystyrene	0.126	3.2	165	4,200	230*	N_2					0.015	0.38		
Polyurethane	0.090	2.3	120	3,050	450	air	60	413			‡	‡		
Teflon	0.002	0.05	600	15,200	380	O_2								
Textiles, nylon	0.004	0.1	7,900	200,000	230*	N_2					0.004	0.10		
Vinyl fabric	0.030	0.8	300	7,600	250						‡‡	‡‡		
WOOD														
Plywood:														
douglas fir comm.	0.248	6.3	64	1,630	250	N_2	50	340	0.018	0.46				
plywood	0.250	6.4	180	4,570	650	O_2								
plywood	0.500	12.7	45	1,140										
douglas fir/urea	0.615	15.6	26	660	250	N_2	50	340	0.019	0.48				
douglas fir/ phenolic	0.623	15.8	6	150	250	N_2	50	340	0.025	0.64				
douglas fir comm.	0.739	18.8	13	330	250	N_2	50	340	0.021	0.53				
plywood	0.750	19.1	200	5,080	3,000	O_2								
Softwood	0.50	12.7	60	1520	650	O_2								
Oak/Maple	0.75	19.1	200	5,080	3,000	O_2								
Spruce	1.62	41	780	19,800	3,000	O_2								
Oak	0.450	11.4	5	130	200	air								
Teak	0.625	15.9	1.8	46	200	air								
Deal	1.250	31.8	2.5	64	200	air								
Soft maple	0.506	12.9	36	910	250	N_2	50	340	0.025	0.64				
Douglas fir	0.856	21.7	15	380	250	N_2	50	340	0.022	0.56				
White pine	0.874	22.2	30	760	250	N_2	50	340	0.021	0.53				
Southern pine	0.784	19.9	11	280	250	N_2	50	340	0.025	0.66				
Hard maple	0.871	22.1	10	250	250	N_2	50	340	0.022	0.56				
White oak	0.866	22.0	10	250	250	N_2	50	340	0.022	0.56				

*TEM 0.1.
‡Smooth, clean cut.
#Some charring.
**Melt on bottom edge.
††Some beading.
‡‡Clean cut.

TABLE 12.7–7—Continued

MATERIAL	THICKNESS		CUTTING RATE		POWER	ASSISTING GAS			KERF WIDTH				HEAT-AFFECTED ZONE	
						Type	Pressure		Inlet		Outlet			
	in	mm	in/min	mm/min	watts		psi	kPa	in	mm	in	mm	in	mm
Hic ory	0.722	18.3	11	280	250	N_2	50	340	0.021	0.53				
Red oak	0.989	25.1	13	330	250	N_2	50	340	0.030	0.76				
Aspen	0.749	19.0	33	840	250	N_2	50	340	0.026	0.66				
Particleboard:														
pine/phenolic	0.522	13.3	2	50	250	N_2	50	340	0.028	0.71				
pine/urea	0.514	13.1	24	610	250	N_2	50	340	0.019	0.48				
Knot:														
southern pine	1.035	26.3	3	75	250	N_2	50	340	0.027	0.69				
red oak	0.830	21.1	11	280	250	N_2	50	340	0.018	0.46				
COMPOSITES														
ABS/Polycarbonate; 50-50	0.140	3.6	40	1,020	250	air	60	410			**	**		
Boron aluminum[§§]	0.008	0.2	30	762	250	O_2	40	280						
Boron/aluminum tape	0.010	0.3	450	11,430	3,000	O_2								
	0.125	3.2	50	1,270	1,000	O_2								
Boron-clay filled	0.015	0.4	270	6,860	250	air	low flow	low flow			*	*		
Boron/epoxy (cured)	0.120	3.0	60	1,520	3,000	O_2								
	0.320	8.1	65	1,650	15,000	O_2								
	0.750	19.1	12	305	4,000	O_2								
Boron fiber composite	0.050	1.3	30	762	260	N_2			0.03	0.76				
	0.050	1.3	9	229	165	A			0.03	0.76				
Boron tape	0.004	0.1	300	7,620	250	O_2	40	280						
Fiberglass epoxy	0.040	1.0	101	2,570	380	O_2								
	0.500	12.7	180	4,570	20,000	O_2								
Glass-reinforced nylon	0.028	0.7	347	8,810	380	O_2								
Graphite epoxy	0.102	2.6	75	1,910	1,000	O_2								
Polyethylene-glass fiber	0.125	3.2	3.6	91	250	air	60	410			**	**		
	0.160	4.1	2.4	61	250	air	60	410			**	**		
	0.190	4.8	1.8	46	250	air	60	410			**	**		
Polyester-glass fiber	0.110	2.8	2.4	61	250	air	60	410			***	***		

[§]Smooth, clean cut.
[§§]Uncured tape.
**Some edge discoloration.
***Small amount charring.

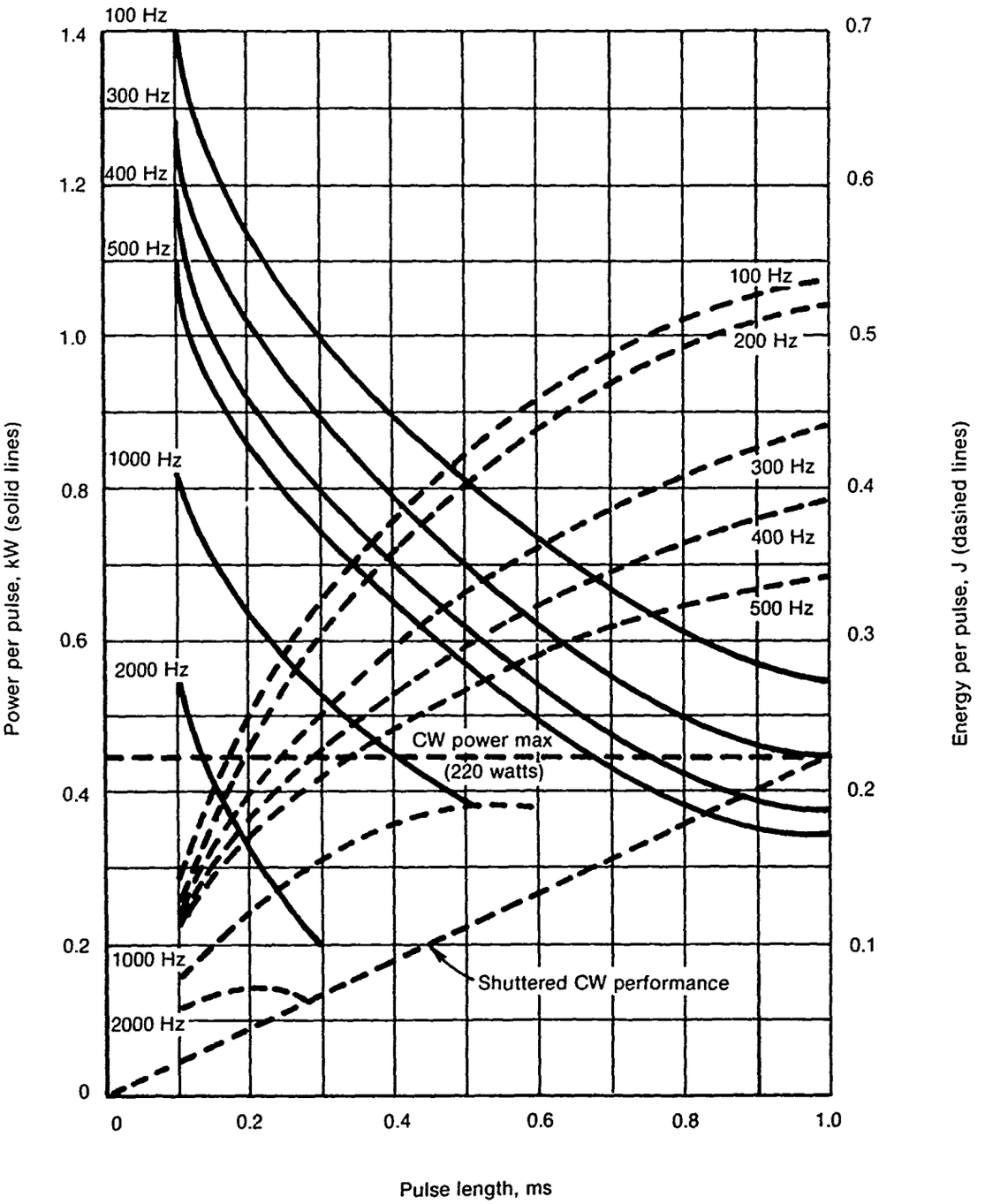


Figure 12.7–5 Pulse power capabilities of 220 watt continuous-wave (CW) CO_2 laser. (Courtesy of Coherent, Inc.)

12.7 Laser Beam Torch—LBT

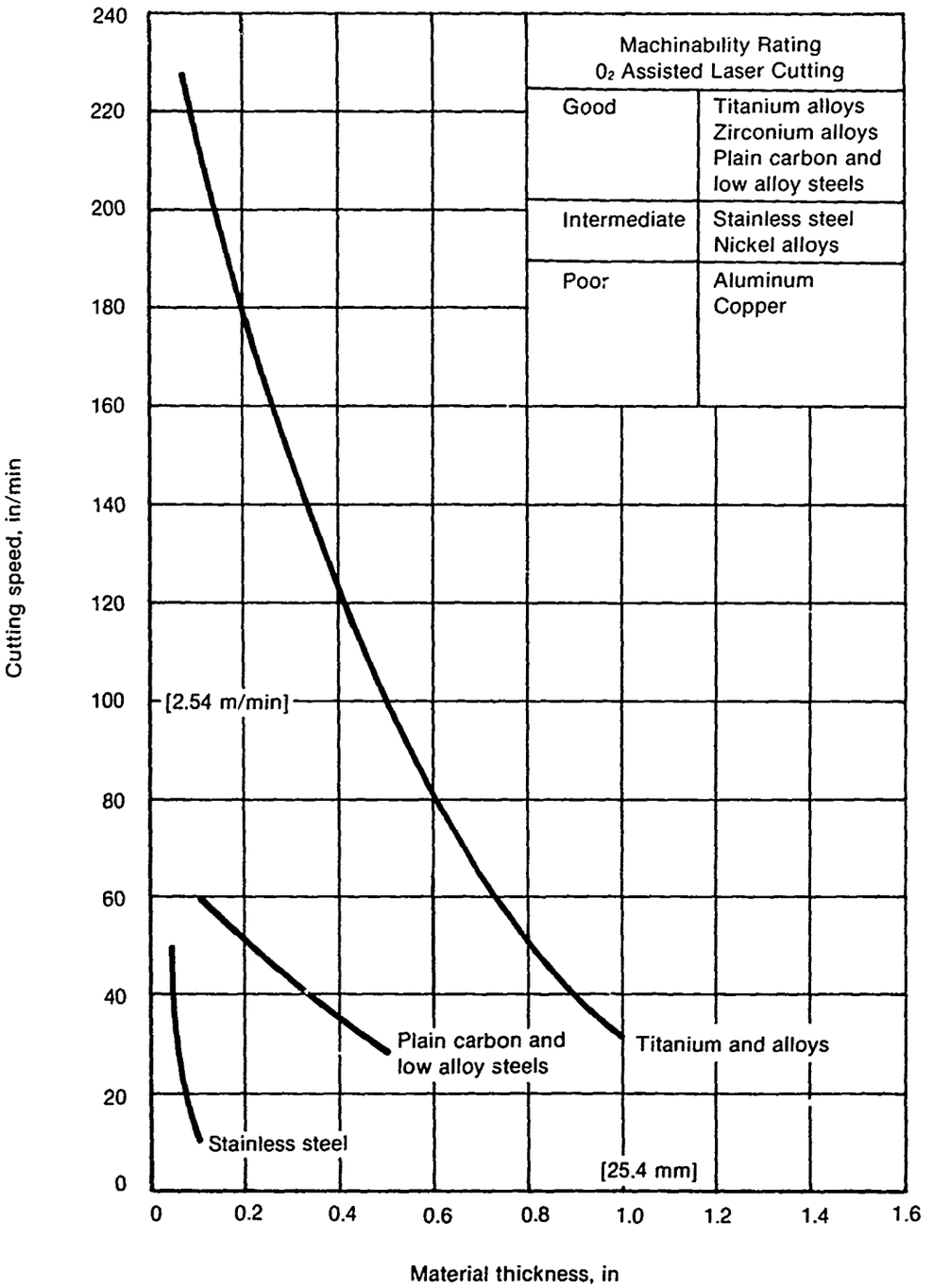


Figure 12.7–6 Cutting rates for 325 watt CO_2 laser with O_2 assist in stainless steel, carbon and low alloy steel, and titanium alloys. (Courtesy of Coherent, Inc.)

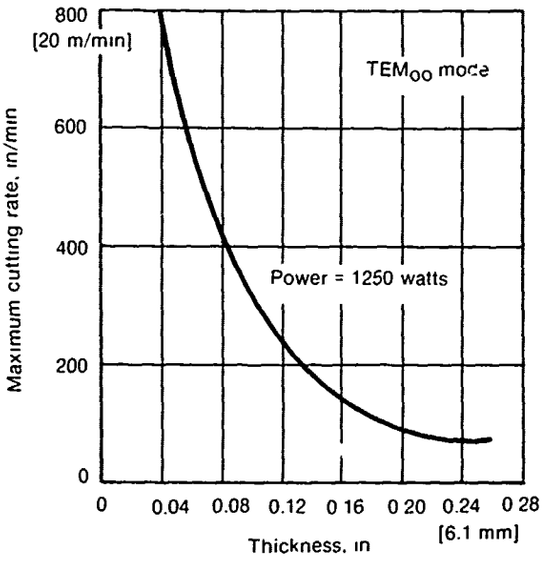


Figure 12.7–7 Maximum material removal rate versus workpiece thickness for CO_2 laser cutting 302 stainless steel at 1250 watts with O_2 assist. Rate inversely proportional to thickness. (Courtesy of GTE-Sylvania)

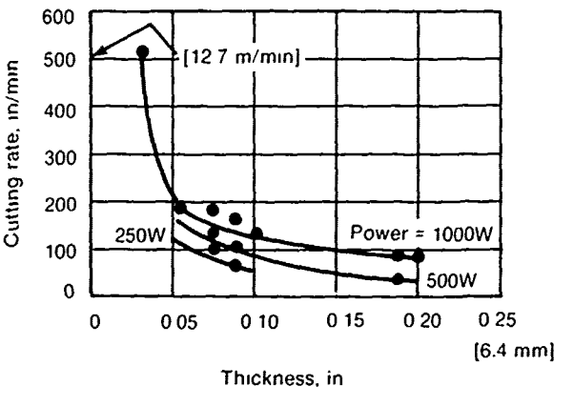


Figure 12.7–9 LBT cutting of low carbon steel using a CO_2 laser with O_2 assist. (W. Hanson and P. Lawryk, Laser machining is now, *Modern Machine Shop* 50 (June 1977), p. 97)

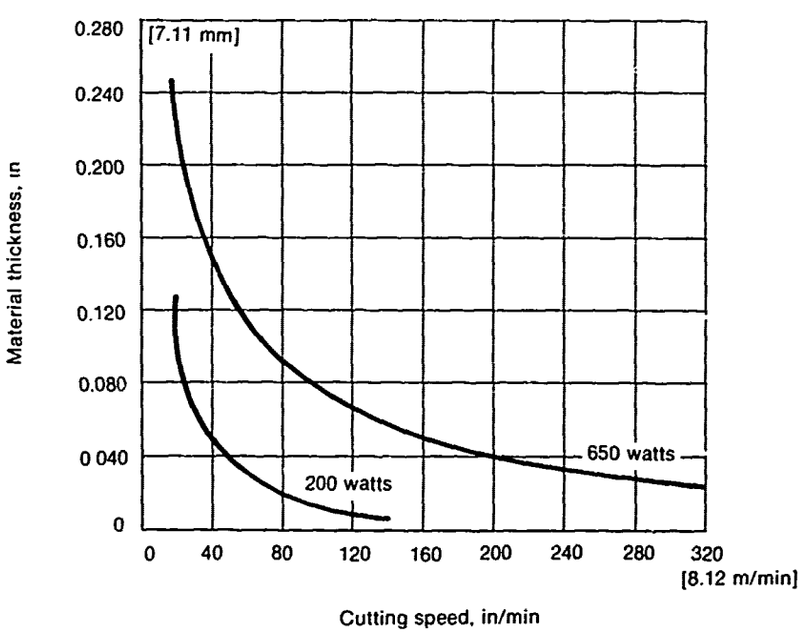


Figure 12.7–8 Maximum material removal rate versus thickness for CW Nd-YAG laser cutting carbon steel with O_2 assist. (Courtesy of Holobeam Laser Inc.)

12.7 Laser Beam Torch—LBT

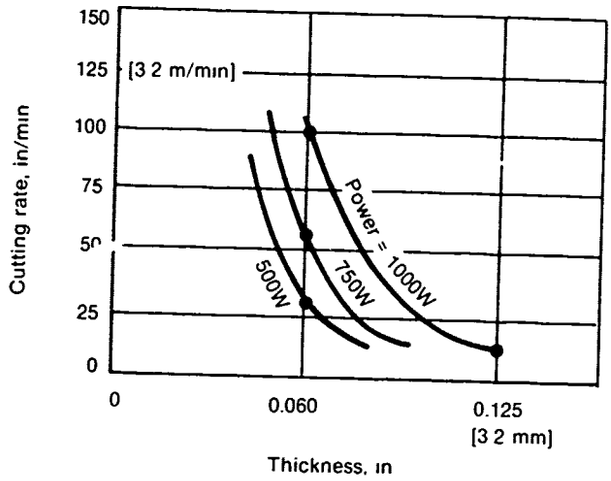


Figure 12.7–10 LBT cutting of titanium using a CO_2 laser with argon gas assist. (W. Hanson and P. Lawryk, p. 97)

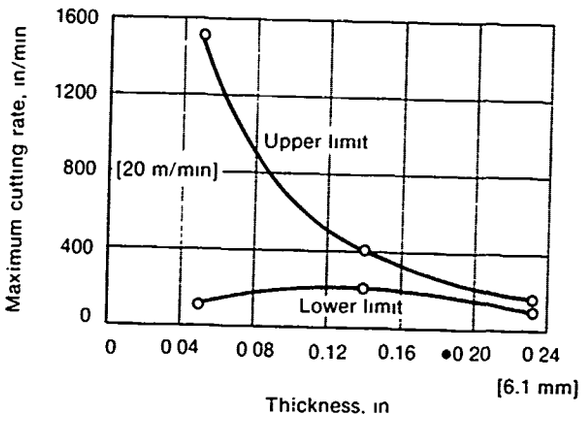


Figure 12.7–12 CO_2 laser cutting rate for Ti-6Al-4V alloy. TEM_{00} mode cutting at 1000 watts with no assisting gas. (Courtesy of GTE-Sylvania)

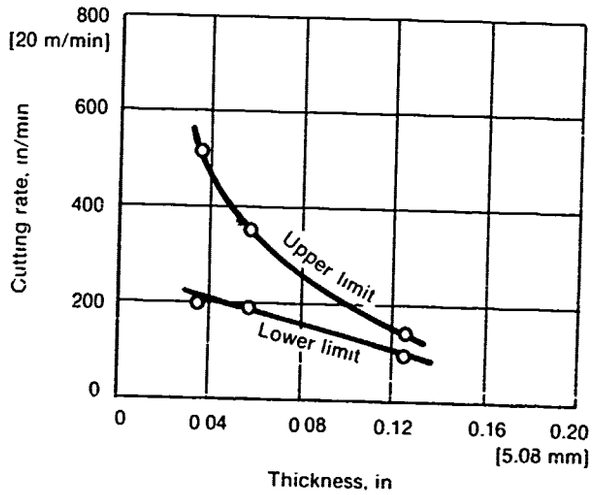


Figure 12.7–11 CO_2 laser cutting rate for 1018 low carbon steel. TEM_{00} mode cutting at 1000 watts with no assisting gas. (Courtesy of GTE-Sylvania)

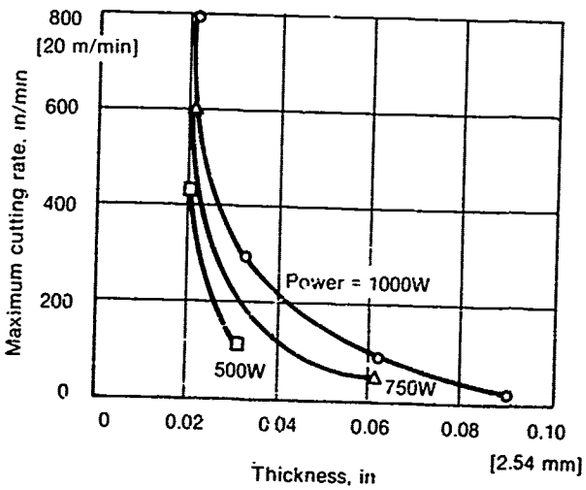


Figure 12.7–13 CO_2 laser cutting rate for 6061 Aluminum alloy. TEM_{00} mode cutting with O_2 assist. (Courtesy of GTE-Sylvania)

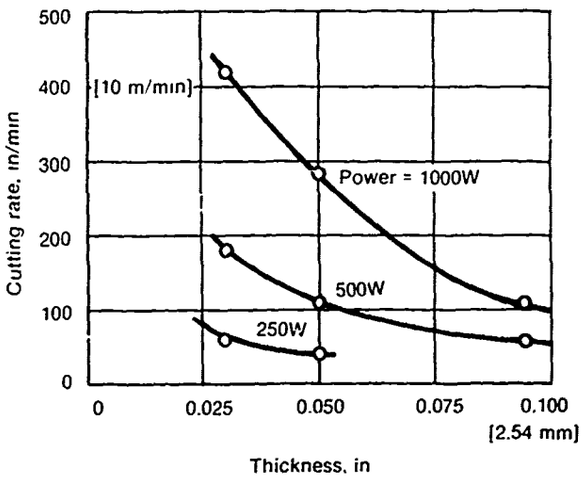


Figure 12.7–14 CO_2 laser cutting rate for Hastelloy alloy X. TEM_{00} mode cutting with O_2 assist. (Courtesy of GTE-Sylvania)

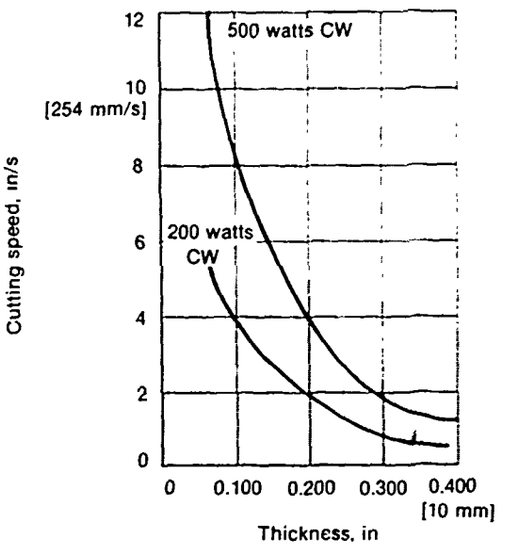


Figure 12.7–16 Acrylic cutting rates with CO_2 laser with air assist. (R. J. Saunders and M. Pasturel, CO_2 laser beam machining of plastic and glass, Technical paper MR74-958, Society of Manufacturing Engineers, Dearborn, MI 1974, p. 8)

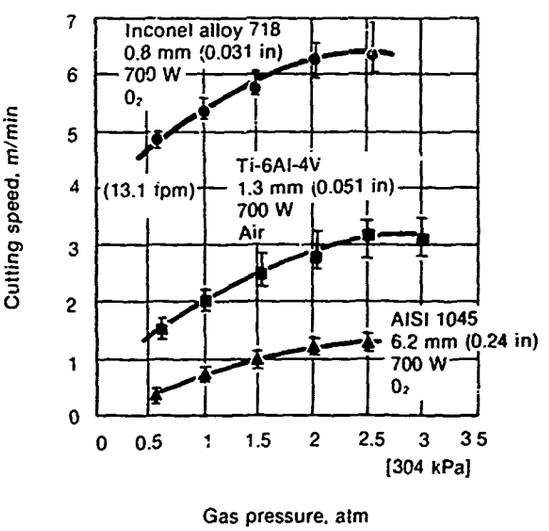


Figure 12.7–15 Cutting speed as a function of gas pressure in cutting Inconel alloy 718, Ti-6Al-4V alloy and AISI 1045 steel. (A. Schachrai and M. Castellani-Longo, p. 466)

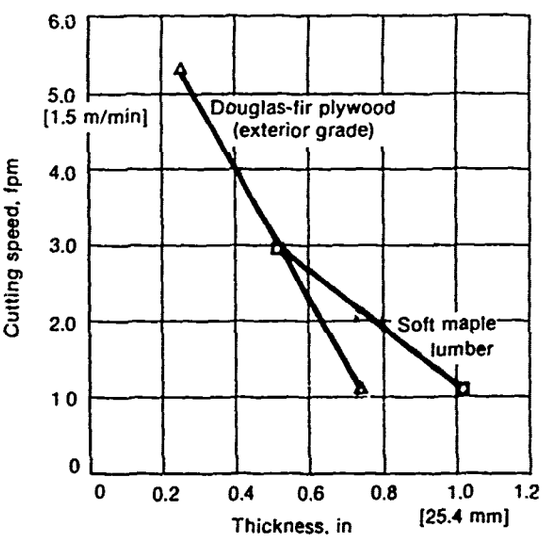


Figure 12.7–17 LBT cutting of plywood and lumber with 250 watt CO_2 laser with 50 psi N_2 gas assist. (C. C. Peters and H. L. Marshall, Cutting wood materials by laser, FPL report 250, Forest Products Laboratory, 1975)

12.7 Laser Beam Torch—LBT

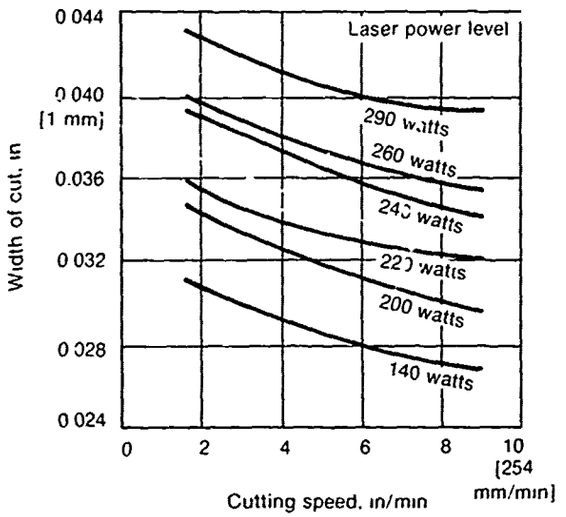


Figure 12.7–18 LBT cutting of parallel-sided slots in 3/4-inch thick plywood for steel rule die manufacture with CO_2 laser using inert gas assist. (Courtesy of Coherent, Inc.)

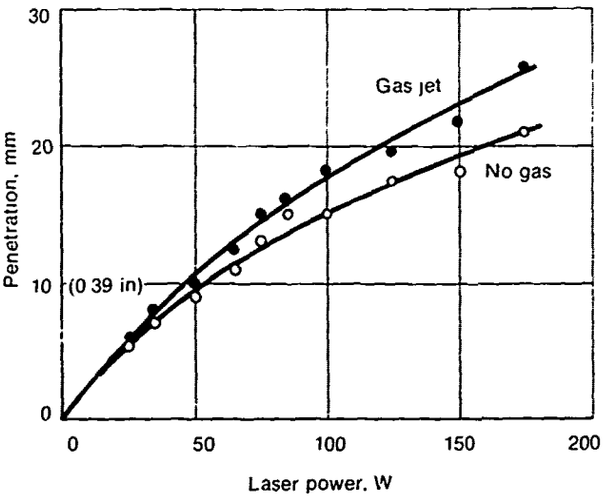
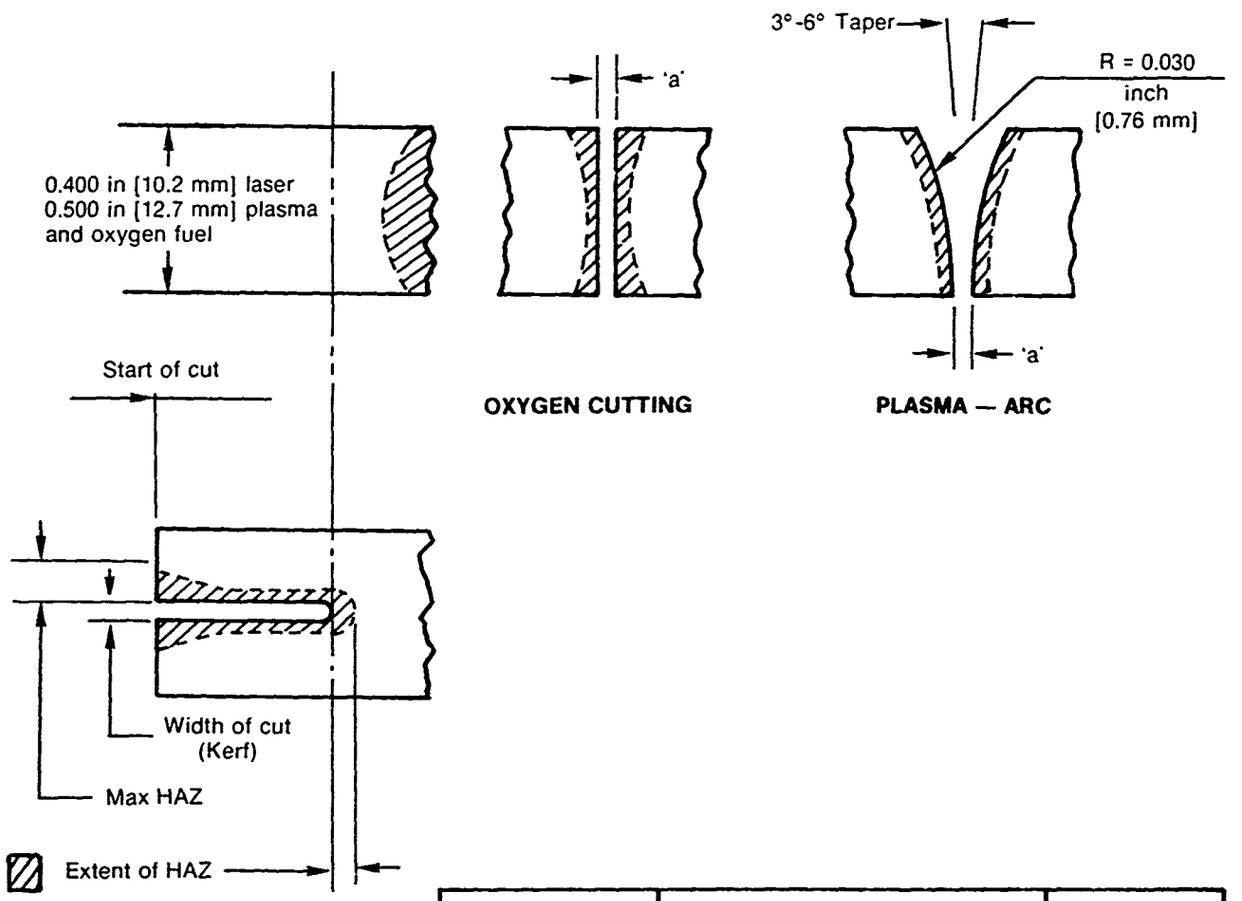


Figure 12.7–19 Penetration of CO_2 laser in boxboard (Perspex) at 200 mm (7.87 in) focal length and 130 mm/min (5.1 in/min) cutting speed. (Courtesy of F. W. Lunau, BOC-Murex Welding Research and Development Laboratories, London)

TABLE 12.7–8 Time Requirements for Drilling 0.004- to 0.005-inch [0.1 to 0.13 mm] Diameter Holes with Nd-YAG Laser

WORK MATERIAL	WORK THICKNESS		DRILL TIME REQUIREMENT min			LAMP CURRENT USED	AVERAGE LASER POWER OF 1.06μm WAVELENGTH	MAXIMUM THICKNESS DRILLED	
	in	mm	Oxygen assist	Air	Argon assist	A	W	in	mm
304 Stainless steel	0.120	3.05	1.46	1.33*	3.69	34	31	0.190	[illegible]
Beryllium	0.049	1.24	4.63	3.41	0.56*	32	24	0.198	[illegible]
3003 Aluminum alloy	0.065	1.65	very long	0.99	0.28*	34	31	0.122	[illegible]
Tungsten	0.033	0.84	0.32	0.27*	1 34	34	31	0.100	[illegible]
Tantalum	0.051	1.30	0.44	0.35*	1.8[illegible]	35	42	0.105	[illegible]
Copper	0.100	2.54	1.63	1.01*	very long	34	31	0.125	[illegible]
AZ 31 Magnesium alloy	0.123	3.12	very long	12.50	0.36*	35	42	0.123	[illegible]
Uranium	0.053	1.35	0.20*	0.22	0.43	35	42	0.125	[illegible]

SOURCE: C. A. Pippin, Metal machining with neodymium laser, *Manufacturing Engineering* 76 (January 1976), p. 39.
*Optimum gas for drilling.



		OXYGEN CUTTING		PLASMA ARC
		Laser	Fuel Gas	
HAZ	in	0.010 to 0.030	0.250	0.100
	mm	0.25 to 0.76	6.4	2.5
Kerf 'a'	in	0.035 to 0.055	0.080	0.312
	mm	0.89 to 1.4	2.0	7.9
EMA	in	0.050	0.375	0.200
	mm	1.27	9.5	5.1

HAZ = Heat Affected Zone
EMA = Edge Machining Allowance

Figure 12.7-20 Comparison of kerfs produced by torch cutting techniques. (Courtesy of Coherent, Inc.)

12.7 Laser Beam Torch—LBT

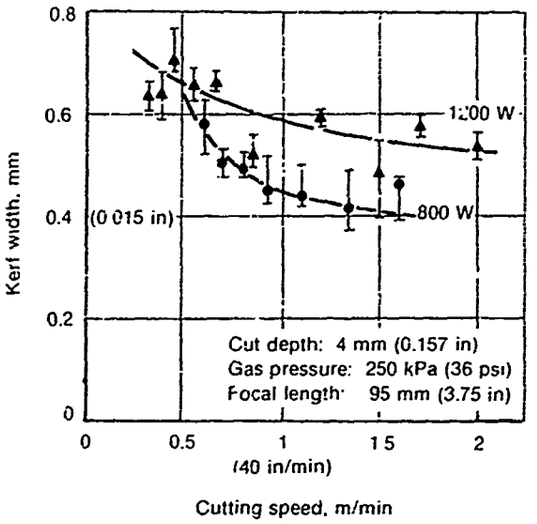


Figure 12.7–21 Kerf width as a function of cutting speed in cutting AISI 316L stainless steel with CO_2 laser torch with O_2 assist. (A. Schachrai and M. Castellani-Longo, p. 466)

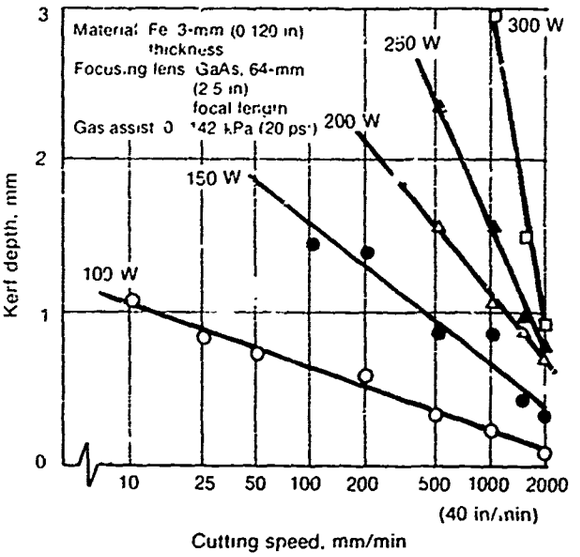


Figure 12.7–23 Relationship between cutting speed and kerf depth with CO_2 laser. (A. Kobayashi, S. Shimakawa and Y. Nagano, Cutting of metals with a 300W CO_2 laser, *Annals of the CIRP*, Vol. 24/1, 1975, p. 122)

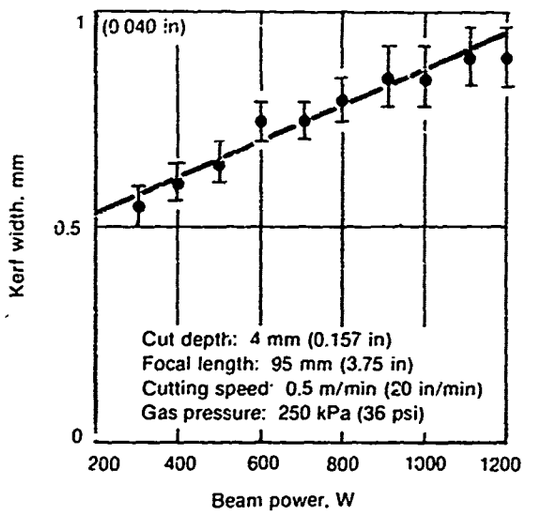


Figure 12.7–22 Kerf width as a function of beam power in cutting AISI 1045 steel with CO_2 laser torch with O_2 assist. (A. Schachrai and M. Castellani-Longo, p. 466)

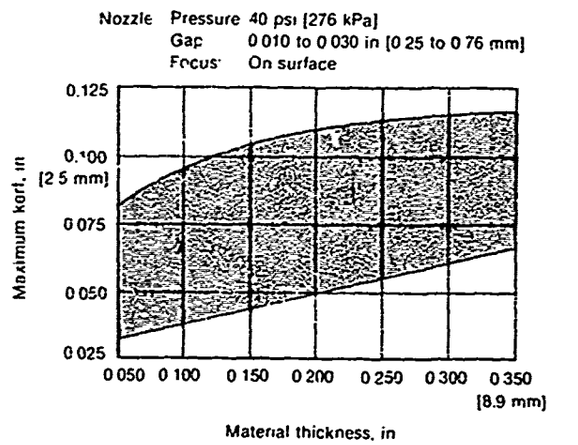


Figure 12.7–24 Maximum kerf width versus material thickness when cutting a variety of metals with 250 watt CO_2 laser. (S. Trink, Laser cutting of aerospace materials, Technical paper EM73-214, Society of Manufacturing Engineers, Dearborn, MI, 1973, p. 18)

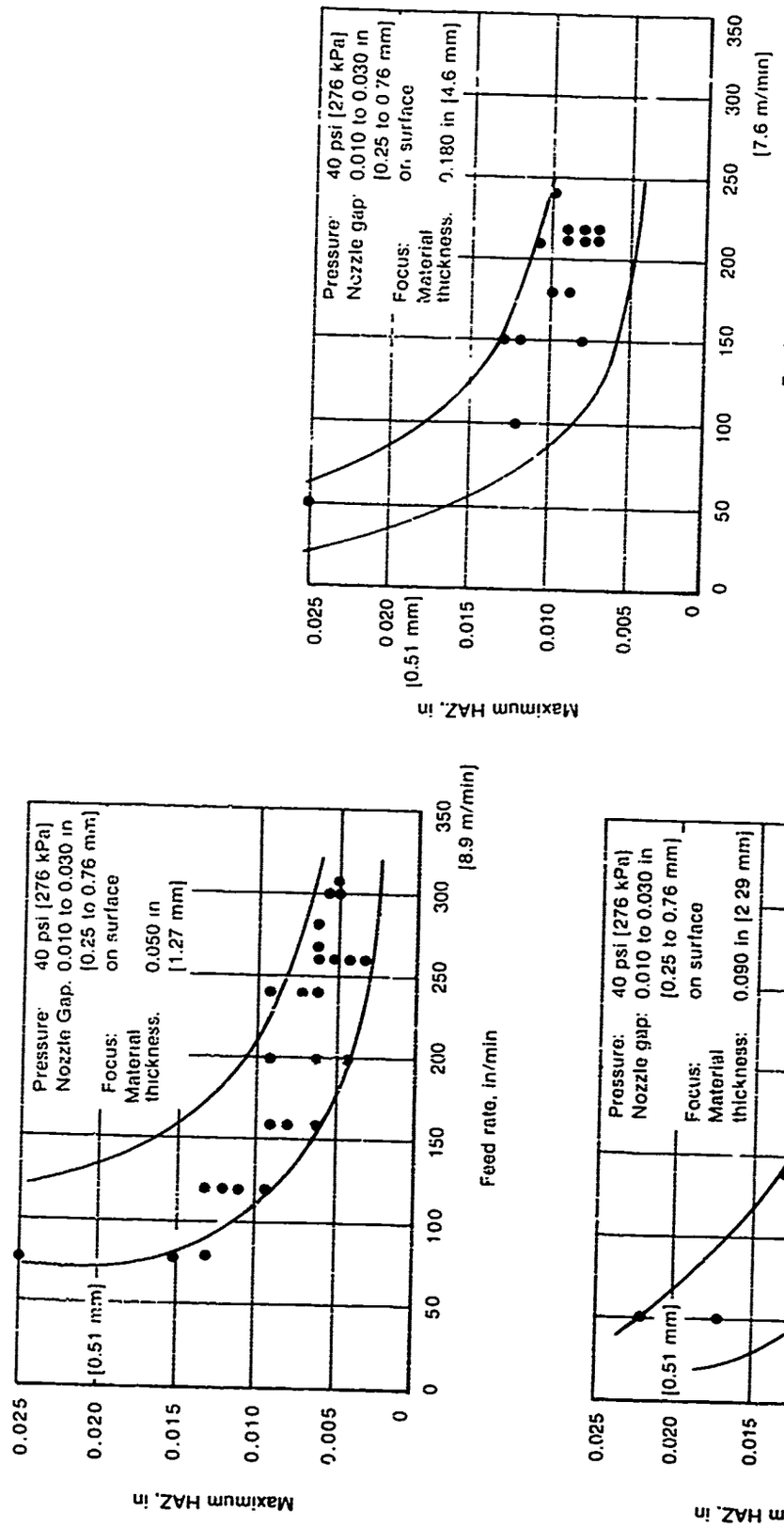


Figure 12.7-25 Maximum heat-affected zone (HAZ) versus feed rate when cutting three different thicknesses of Ti-6Al-6V-2Sn alloy with 250 watt CO_2 laser with O_2 gas assist. (S. Trink, p. 18–19)

12.7 Laser Beam Torch—LBT

SPECIFIC APPLICATIONS DATA

TABLE 12.7-9 Specific Applications Data for Laser Beam Torch

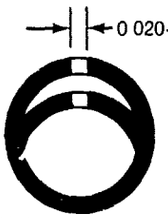
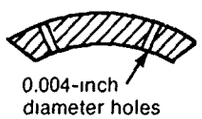
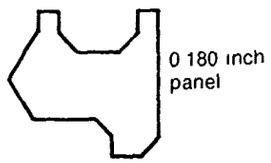
Work material:	**Polyethylene Tubing (bi-wall)**	**Glass Contact Lens**	**TI-6AI-6V-2Sn**
Workpiece configuration:	 Hole spacing on 6-to 24-inch centers		
Laser equipment type:	CO_2	CO_2	CO_2
wavelength, μm·	10.6	10.6	10.6
power:	250 W	50 W	250 W
gas.			O_2
gas pressure, psi·			40
Operating conditions power level:			250 W
beam mode:	CW	CW	CW
pulse length, ms:	5 to 15		
cycle time·		1.5 s/lens	
feed rate, in/min.			140
Tolerance, in:			
Remarks:	Drill during extrusion using optical tracking. Extrusion up to 300 fpm. No deburring. No residue. Wall thicknesses range from 0.010 to 0.040 inch. Pulse length depends on hole in outer wall; some holes through both walls.	5 to 15 holes. NC controlled	Good saving by nesting parts.

TABLE 12.7-9—Continued

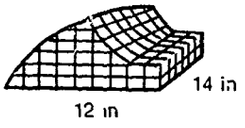
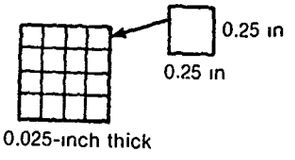
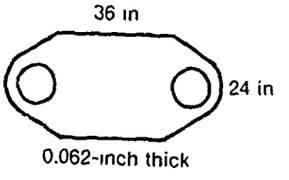
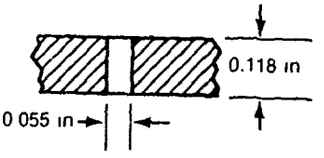
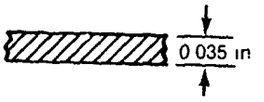
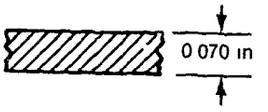
Work material:	Aluminum Honeycomb	Fired Ceramic Alumina	Stainless Steel Heat Exchanger Component
Workpiece configuration:			
Laser equipment type:	CO_2	CO_2	CO_2
wavelength, μm:	10.6	10.6	10.6
power:	1,000 W	50 W	2,500 W
gas:	O_2	N_2	O_2
gas pressure, psi:	40		
Operating conditions power level:	1,000 W	50 W	1,000 W
beam mode:	CW	Pulsed	CW
pulse length, ms:		0.5	
cycle time:			
feed rate, in/min:	90	2 to 4 in/s	450
Tolerance, in:		No HAZ	
Remarks:	In contour cuts, no burrs or bent combs.	Scribing with closely spaced holes, 0.003-inch dia. by 0.008-inch deep.	LBT substitute for large blanking dies. Vacuum-chuck worktable with NC motion.

TABLE 12.7-9—Continued

Work material	SAE 1008 Steel	Carbon Steel	Steel
Workpiece configuration			
Laser equipment type.	YAG	YAG	YAG
wavelength, μm:	1.06	1.06	1.06
power.	70 J	200 W	600 W
gas:	O_2	yes	O_2
gas pressure, psi:			
Operating conditions power level	55 J	200 W	600 W
beam mode.	Pulsed multi	CW multi	Multi
pulse length, ms:	1		
cycle time:	10 shots at 1 pps		
feed rate, in./min		50	50
Tolerance, in.			
Remarks:		Slitting	Slitting

Plasma Beam Machining—PBM 12.8

PROCESS SUMMARY

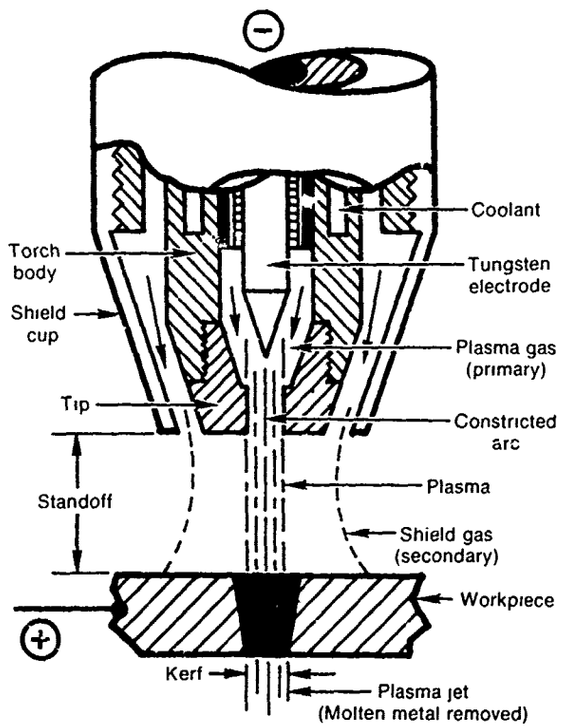


Figure 12.8-1 PBM schematic

Principles

Plasma beam machining (PBM) removes material by utilizing a superheated stream of electrically ionized gas (see figure 12.8-1). The 20,000° to 50,000°F [11,000° to 28,000°C] plasma is created inside a water-cooled nozzle by electrically ionizing a suitable gas such as nitrogen, hydrogen, argon, or mixtures of these gases. Since the process does not rely on the heat of combustion between the gas and the workpiece material, it can be used on almost any conductive metal. Generally, the arc is transferred to the workpiece which is made electrically positive. The plasma—a mixture of free electrons, positively-charged ions and neutral atoms—is initiated in a confined, gas-filled chamber by a high-frequency spark. The high-voltage direct-current power sustains the arc, which exits from the nozzle at near sonic velocity. The high-velocity gases blow away the molten metal "chips." Dual-flow torches use a secondary gas or water shield to assist in blowing the molten metal out of the kerf, giving a cleaner cut. Water shield or injection is sometimes used to assist in confining the arc, blasting away the scale and reducing smoke. Greater nozzle life and faster cutting speeds accompany use of water-injection-type torches. Control of nozzle standoff from the workpiece is important. One electrode size can be used to machine a wide range of materials and thicknesses by suitable adjustments to the power level, gas type, gas flow rate, traverse speed and flame angle. PBM is sometimes called plasma arc machining (PAM) or plasma arc cutting (PAC).

Practical Applications

High cutting speed and the ability to cut exotic metals are the greatest operational advantages of PBM. Profile cutting of metals, particularly of stainless steel and aluminum, has been the most prominent commercial application; however, mild steel, alloy steel, titanium, bronze and most metals can be cut cleanly and rapidly. Multiple-torch cuts are possible on programmed or tracer-controlled cutting tables on plates up to 6-inches [150 mm] thick in stainless steel. Smoothness of cut with freedom from contaminants is an advantage. Well-attached dross on the underside of the cut can be a problem. The transfer arc is used for the thick cuts in metals. Applications for surface heat treatment exist, and the plasma arc is widely used for metal joining. The plasma torch also is used for "punching" holes, as an assist to turning, or for grooving. Plasma cutting has become popular as a maintenance tool since the development of LO-AMP™ portable plasma cutting equipment.

Operating Parameters

TABLE 12.8-1 Typical Values for PBM Operating Parameters

Power supply	
type:	Direct current
wattage:	Up to 200 kW
current:	50 to 1,000 A
Primary gas	
type:	Argon-nitrogen (80%-20%), hydrogen
flow:	15 to 200 ft³/hr [0.42 to 5.66 m³/hr]
Shielding gas	
type:	Nitrogen, oxygen, water, compressed air, CO_2
flow:	Up to 400 ft³/hr [11.3 m³/hr]
Water shield flow (in place of shielding gas):	Up to 15 gal/hr [56.8 L/hr]
Plasma temperature:	20,000° to 50,000°F [11,100° to 27,800°C]
Cutting speed:	2 to 240 in/min [50 to 6,100 mm/min]
Standoff distance:	0.25 to 3 inches [6.4 to 9.5 mm]
Nozzle orifice size:	0.062- to 0.25-inch [1.59 to 6.35 mm] diameter (figure 12.8-2)
Kerf width:	0.060- to 0.090-inch [1.52 to 2.29 mm] thin plate 0.188 inch [4.76] for 1-inch [25.4 mm] plate 0.75 inch [19 mm] for 6-inch [152 mm] plate
Kerf angle	
normal:	2° to 7°
special:	1° to 2°
Accuracy:	±0.031 inch [0.81 mm] on 0.25- to 1.375-inch [6.4 to 35 mm] plate ±0.125 inch [3.2 mm] on 6- to 8-inch [152 to 203 mm] plate
Corner radii:	0.156 inch [3.9 mm] minimum (increases with increasing cutting speeds to 1.50 inches [38 mm] at 240 in/min [6,100 mm/min]

12.8 Plasma Beam Machining—PBM

Material Removal Rates and Tolerances

Profile cutting can be done at 30 inches per minute [760 mm/min] on 1-inch [25.4 mm] thick aluminum plate, while 1/4-inch [6.4 mm] thick carbon steel can be cut at 160 inches per minute [4,060 mm/min]. The use of water injection can increase the carbon steel cutting rates to 240 inches per minute [6,100 mm/min] for 3/16-inch [4.76 mm] thick plate. Tables 12.8-2 and 12.8-5 through 12.8-7 show the range of cutting speeds for PBM of various materials and thicknesses. Table 12.8-9 and figure 12.8-4 contain feed and speed data for plasma arc turning.

The taper on the sides of the cut ranges from 2 to 7 degrees with the straight side determined by the direction of the cut. With special selection and controls, the taper can be held to 1 to 2 degrees. The kerf width usually is 3/32 to 3/16 inch [2.38 to 4.76 mm] for metals less than 1-inch [25.4 mm] thick and 3/8 to 3/4 inch [9.5 to 19 mm] for metals up to 6-inches [150 mm] thick. Corner radius is a minimum of 5/32 inch [3.97 mm] on thinner plates. Tolerances for slots and holes ordinarily range from ±1/32 inch [±0.81 mm] on 1/4-to 1-3/8-inch [6.4 to 35 mm] thick plates to ±1/8 inch [±3.18 mm] on 6-inch [152 mm] thick plates.

Surface Technology

Grooving is not as severe as in gas torch cutting, and surface roughness can be as good as 32 microinches R_a [0.8 μm]. The usual roughness is 63 to 125 microinches R_a [1.6 to 3.2 μm]. A heat-affected zone can range from 1/32- to 3/16-inch [0.81 to 4.76 mm] deep, depending on the workpiece thermal properties, the work speed and the depth of cut. Sometimes an increase in hardness will accompany the heat-affected zone and will require an edge-finishing operation. In many applications, the cut edge may be adequate for the functional purpose; however, an allowance of 1/16 inch [1.6 mm] for finishing is typical for PBM.

Equipment and Tools

Hand-held plasma torches and small portable equipment are available, as are NC or CNC programmable motion-controlled, multiple-torch arrangements. Optical followers and table sizes up to 44 by 82 feet [13.4 by 25 m] are used, with cutting speeds controllable from 2 to 240 inches per minute [50 to 6,100 mm/min]. Advanced systems with water injection, water shielding or water beds to catch the dross are available. In addition to flat contour cutting, attachments for lathe turning, grooving or gouging are made (see TAM).

Some advanced plasma cutting systems are designed for mounting on large NC shape-cutting machines and are equipped with torch standoff controls that automatically find and maintain the correct torch standoff from the plate.

Tooling is simple because there is little load reaction from the torch.

Machining Characteristics

Eye shielding, and noise and fume control are needed to meet workplace environmental requirements. High-flow water shield (sometimes called a water muffler) may be used to recirculate cutting table water at a high flow rate (1,000 gallons per hour [3,780 L/hr]) through a ring mounted around the torch head. This provides a shield or curtain which reduces most of the light, smoke and noise created by the plasma cutting operation. Introduction of a dye into the water can reduce the glare of the arc.

SELECTED DATA

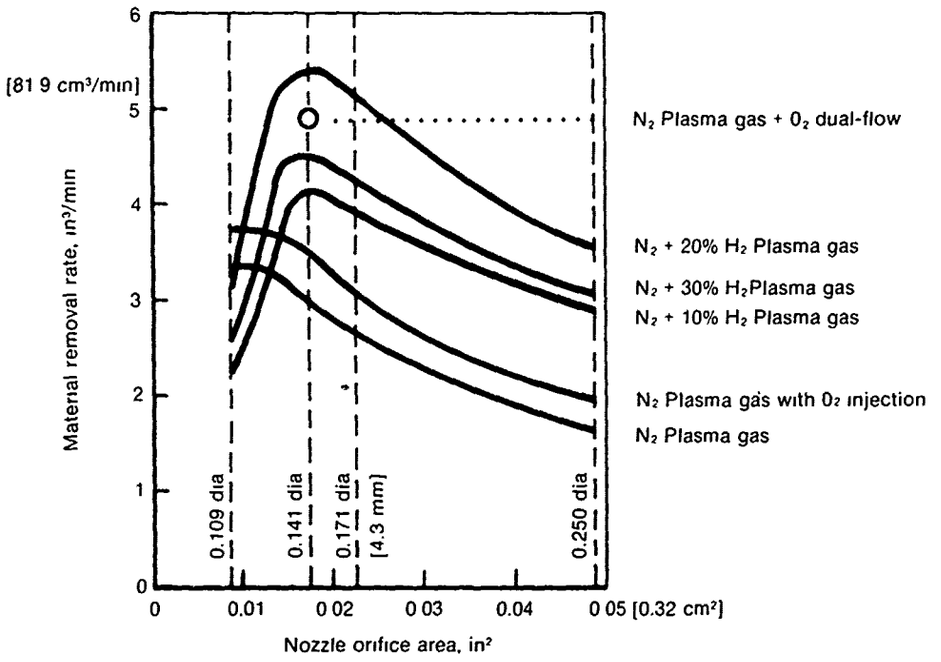


Figure 12.8–2 Material removal rates for PBM with various gases and nozzle orifice sizes. (R. K. Springborn, ed., *Non-traditional machining processes*, Dearborn, MI: American Society of Tool and Manufacturing Engineers, 1967, p. 163)

TABLE 12.8–2 Plasma Cutting Guide for Common Steel, Stainless Steel and Aluminum

WORKPIECE THICKNESS		CUTTING SPEED		POWER SELECTION Amperage, A		
in	mm	in/min	cm/min	Steel	Stainless steel	Aluminum
0.25	6.35	20	51	100		
		40	102	110		
		70	178	150	105	
		100	254	200	140	
		150	381		210	135
		160	406	280		
		200	508	420		
		430	1,092			550
0.50	12.70	20	51	170	135	
		40	102		190	120
		70	178	260	250	180
		100	254		270	275
		135	343	500		
		150	381		700	450
		175	445	1,000		
		210	533		1,000	
		280	711			1,000

SOURCE: J. A. Bagley, Plasma arc cutting, Technical paper MR69-578, Society of Manufacturing Engineers, Dearborn, MI, 1969, p. 23.

12.8 Plasma Beam Machining—PBM

TABLE 12.8–2—Continued

WORKPIECE THICKNESS		CUTTING SPEED		POWER SELECTION		
				Amperage, A		
in	mm	in/min	cm/min	Steel	Stainless steel	Aluminum
0.75	19.05	10	25	180	130	
		20	51	220	155	100
		33	84	280		
		40	102	330	235	150
		70	178	600	420	275
		100	254	875	620	400
1	25.40	10	25	250	175	115
		20	51	270	210	140
		30	76		270	270
		40	102	530	350	
		70	178	900		
		80	203	1,000	540	520
		100	254			550
		110	279		1,000	
		135	343			1,000
1.25	31.80	10	25	300	210	140
		20	51	420	300	190
		40	102	650	460	300
		70	178	1,100	800	500
		100	254		1,140	620
1.50	38	10	25	400	280	180
		20	51	590	420	270
		40	102	875	620	400
		70	178		1,000	550
		100	254			750
2	50	5	13	450	320	210
		10	25	600	420	275
		20	51	850	610	390
		40	102		950	600
		70	178			800
2.5	63.5	5	13	585	410	235
		10	25	785	550	320
		20	51		820	470
3	76	5	13	730	510	295
		10	25	970	675	385
		20	51		1,020	585
3.5	89	5	13	790	550	320
		10	25	1,050	730	420
		20	51		1,110	640
4	100	5	13	970	675	385
		10	25		900	520
		20	51			800
4.5	114	5	13		900	850
5	127	3	7.6		1,100	900
5.5	140	3	7.6		1,100	1,000

TABLE 12.8–3 Nozzle Size and Gas Flow Selection

REQUIRED AMPERE RANGE	NOZZLE SIZE		GAS FLOW*				MAXIMUM AMPERAGE†
			N_2		H_2		
A	in	mm	ft³/hr	m³/hr	ft³/hr	m³/hr	A
0 to 200	0.125	3.18	100	2.83	8	0.23	225
200 to 275	0.140	3.56	110	3.11	10	0.28	300
275 to 300	0.161	4.09	120	3.40	12	0.34	400
350 to 400	0.187	4.75	150	4.25	15	0.42	550
450 to 650	0.218	5.54	180	5.10	18	0.51	700
over 650	0.250	6.35	225	6.37	20	0.57	1,100

SOURCE: J. A Bagley, p. 23.

*Gas mix of N_2 and H_2 measured at 70 psi [480 kPa] input to 25 feet [7.6 m] of 3/8-inch [9.5 mm] diameter hose.

†Do not exceed this amperage for each nozzle size. To estimate power consumption multiply amperes by 200.

TABLE 12.8–4 Plasma Arc Gouging Power and Speed in 5086 Aluminum Alloy
(Constant 1/8-inch [3.2 mm] standoff, torch angle of 45°, and nitrogen gas)

SPEED		GROOVE SIZE				MATERIAL REMOVAL RATE	
		Width		Depth			
in/min	mm/min	in	mm	in	mm	in³/min	cm³/min
40	1,016	0.56	14.2	0.25	6.4	4.29	70.3
50	1,270	0.63	16.0	0.22	5.6	4.35	71.3
60	1,524	0.50	12.7	0.19	4.8	4.31	70.6
70	1,778	0.47	11.9	0.16	4.1	3.70	60.6
80	2,032	0.44	11.2	0.13	3.3	3.10	50.8
90	2,286	0.41	10.4	0.13	3.3	3.60	59.0
POWER kVA		SPEED: 50 in/min [1270 mm/min]					
35.5		0.47	11.9	0.22	5.6	3.90	63.9
38.9		0.56	14.2	0.24	6.1	5.10	83.6
42.0		0.59	15.0	0.26	6.6	5.80	95.1
		SPEED: 60 in/min [1524 mm/min]					
35.8		0.50	12.7	0.16	4.1	3.30	54.1
37.9		0.53	13.5	0.16	4.1	3.50	57.4
42.6		0.56	14.2	0.19	4.8	4.60	75.4

SOURCE: J. F. Alban, Jr., Plasma arc gouging of aluminum, *Welding Journal* 55 (November 1976), p. 956–57.

12.8 Plasma Beam Machining—PBM

TABLE 12.8–5 Cutting Speeds for Plasma Beam Machining

MACHINING CONDITIONS	MATERIAL THICKNESS in / mm	CUTTING SPEED in/min / m/min					
		Carbon Steel		Stainless Steel		Aluminum	
		Best	Max.	Best	Max.	Best	Max.
100 amperes*	0.25	40	80	50	100	60	120
	0.50	16	25	20	30	28	43
Primary gas: N_2	0.75	NR	NR	12	15	15	19
at 55 cfh	1.00	NR	NR	9	11	10	12
30 psi							
	6.4	1.02	2.03	1.27	2.54	1.52	3.05
Secondary gas CO_2	12.7	0.41	0.64	0.51	0.76	0.71	1.09
at 210 cfh	19.0	NR	NR	0.30	0.38	0.38	0.48
40 psi	25.4	NR	NR	0.23	0.28	0.25	0.30
200 amperes†	0.25	50	100	65	135	75	155
	0.50	30	40	50	70	60	85
Primary gas: N_2	0.75	20	30	35	50	40	55
at 70 cfh	1.0	15	20	20	26	26	35
30 psi	1.5	NR	NR	12	16	18	24
	6.4	1.27	2.54	1.65	3.43	1.90	3.94
Secondary gas CO_2	12.7	0.76	1.07	1.27	1.78	1.52	2.16
at 210 cfh	19.0	0.51	0.76	0.89	1.27	1.02	1.40
40 psi	25.4	0.38	0.51	0.51	0.66	0.66	0.89
	38.1	NR	NR	0.30	0.40	0.46	0.51
400 amperes‡	0.5	40	65	75	120	90	150
	1.0	30	40	40	55	50	70
Primary gas: N_2	1.5	20	30	25	38	35	50
at 50 cfh	2.0	14	23	17	28	28	45
20 psi	2.5	10	13	12	15	16	20
	3.0	6	7	8	10	10	12
Secondary gas: CO_2	12.7	1.02	1.65	1.91	3.05	2.29	3.81
at 210 cfh	25.4	0.76	1.07	1.02	1.40	1.27	1.78
40 psi	38.1	0.51	0.76	0.64	0.97	0.89	1.27
	50.8	0.36	0.50	0.49	0.71	0.71	1.14
	63.5	0.25	0.36	0.30	0.50	0.41	0.61
	76.2	0.15	0.18	0.20	0.25	0.25	0.28

SOURCE: Data courtesy of Thermal-Dynamics Corp.

NOTES: NR = Not recommended.

*Minimum speed = 20 in/min [0.51 m/min] on 0.25-inch [6.4 mm] thick material. Maximum thickness for piercing applications is 0.375 inch [10 mm].

†Maximum thickness for piercing applications is 0.5 inch [13 mm]

‡Maximum thickness for piercing applications is 0.75 inch [19 mm].

TABLE 12.8–6 Cutting Speeds with Water-Injection PBM

MACHINING CONDITIONS	MATERIAL THICKNESS	CUTTING SPEED in/min m/min					
		Carbon Steel		Stainless Steel		Aluminum	
	in mm	Best	Max.	Best	Max.	Best	Max.
300 amperes*	0.25	60	110	75	130	85	145
	0.50	40	60	50	70	55	80
Primary gas: N_2	0.75	30	40	40	55	55	75
at 75 cfh	1.00	20	25	25	35	40	60
30 psi	1.25	12	15	19	23	24	29
	1.50	12	15	15	18	20	25
Water injection							
at 8 to 15 gal/hr	6.4	1.52	2.79	1.91	3.30	2.16	3.68
	12.7	1.02	1.52	1.27	1.78	1.40	2.03
	19.0	0.76	1.02	1.02	1.40	1.40	1.91
	25.4	0.51	0.64	0.64	0.89	1.02	1.52
	31.8	0.30	0.38	0.46	0.56	0.61	0.74
	38.1	0.30	0.38	0.36	0.46	0.51	0.64

SOURCE: Data courtesy of Thermal-Dynamics Corp

*Maximum thickness for piercing applications is 0.625 inch [16 mm]

TABLE 12.8–7 Cutting Speeds for PBM of Sheet Metals

MACHINING MATERIAL CONDITIONS	THICKNESS		CUTTING SPEED			
			Mild Steel		Stainless Steel	
	in	mm	in/min	m/min	in/min	m/min
50 to 100 amperes	0.062	1.5	275	7.0	280	7.1
	0.125	3	190	4.8	195	5.0
Primary gas: N_2	0.188	5	80	2.0	85	2.1
at 15 cfh						
35 to 40 psi	0.250	6	65	1.6	70	1.8
	0.375	10	50	1.3	55	1.4
Secondary gas: CO_2	0.500	12	35	0.9	40	1.0
at 150 cfh						
45 to 50 psi						

SOURCE: Data courtesy of W. A. Whitney Co

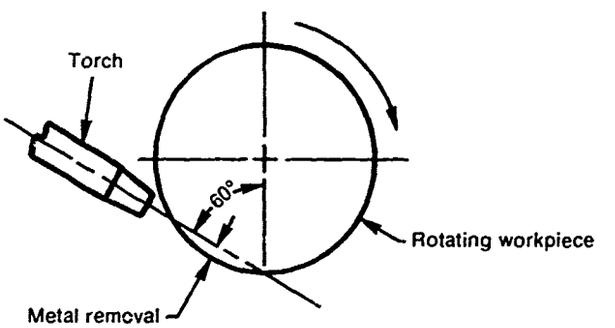
TABLE 12.8–8 Tolerances for PBM Hole Piercing
(For 0.156-inch [4 mm], 9-gage steel)

HOLE DIAMETER		INCLUDED ANGLE	DIAMETER TOLERANCE		OUT-OF-ROUND	
in	mm	degrees	in	mm	in	mm
0.188	4.76	10	±0.01	±0.25	0.01	0.25
0.250	6.35	2	±0.01	±0.25	0.01	0.25
0.312	7.94	2	±0.01	±0.25	0.01	0.25
0.375	9.53	4	±0.01	±0.25	0.01	0.25
0.437	11.10	4	±0.02	±0.51	0.01	0.25

12.8 Plasma Beam Machining—PBM

TABLE 12.8–9 Plasma Arc Turning Parameters

MATERIAL	TYPE OF CUT	CURRENT DCSP	ARC VOLTAGE	ROTATING SPEED		FEED PER REVOLUTION		METAL REMOVAL RATE		POWER	
		A	V	fpm	m/min	in	mm	in³/min	cm³/min	hp/in³/min	kW/cm³/min
Inconel	Rough	300	100	40	12	0.160	4.1	4.0	65.6	9.0	0.41
	Smooth	170	90	75	23	0.050	1.3	1.5	24.6	15.0	0.69
Rene 41	Rough	325	95	52	16	0.160	4.1	5.0	81.9	8.0	0.37
	Smooth	240	90	104	32	0.080	2.0	2.0	32.8	15.0	0.69
Hastelloy alloy C	Rough	200	100	30	9	0.100	2.5	3.5	57.4	7.0	0.32
	Smooth	140	130	60	18	0.050	1.3	1.5	24.6	15.0	0.69
Precipitation-hardening stainless steels	Rough	300	90	50	15	0.160	4.1	4.5	73.8	8.0	0.37
	Smooth	170	92	200	61	0.040	1.0	2.0	32.8	15.0	0.69



SOURCE: J A. Bagley, p. 25.

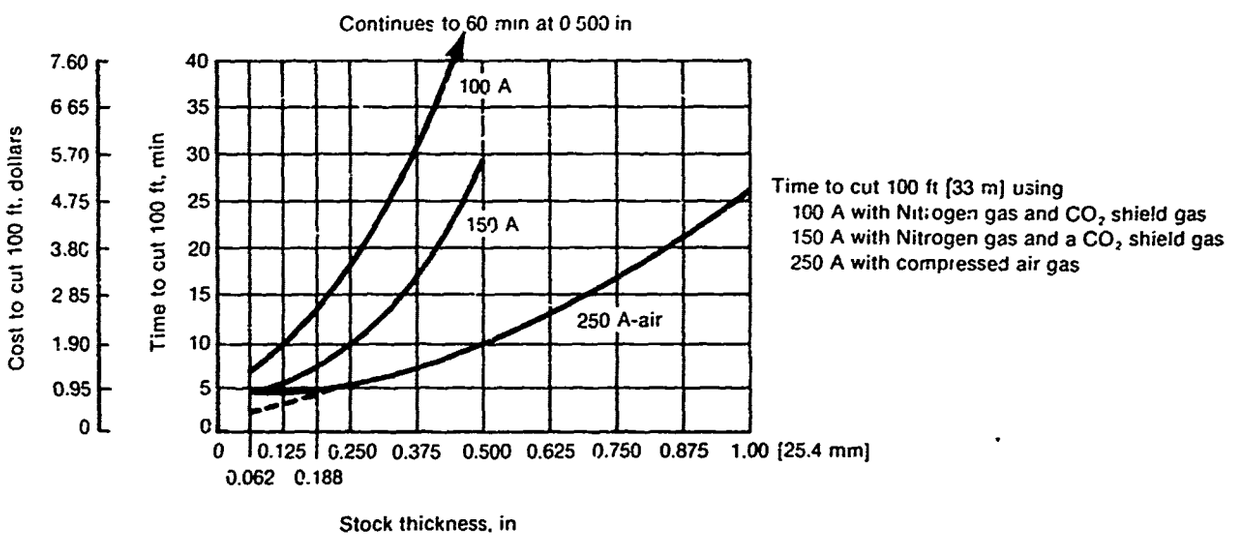


Figure 12.8–3 Cost and time versus thickness in cutting mild steel with plasma arc. Cost includes gas, perishable parts and electricity, at prevailing rates in 1978, but does not include labor cost for time indicated. (Courtesy of W. A. Whitney Company)

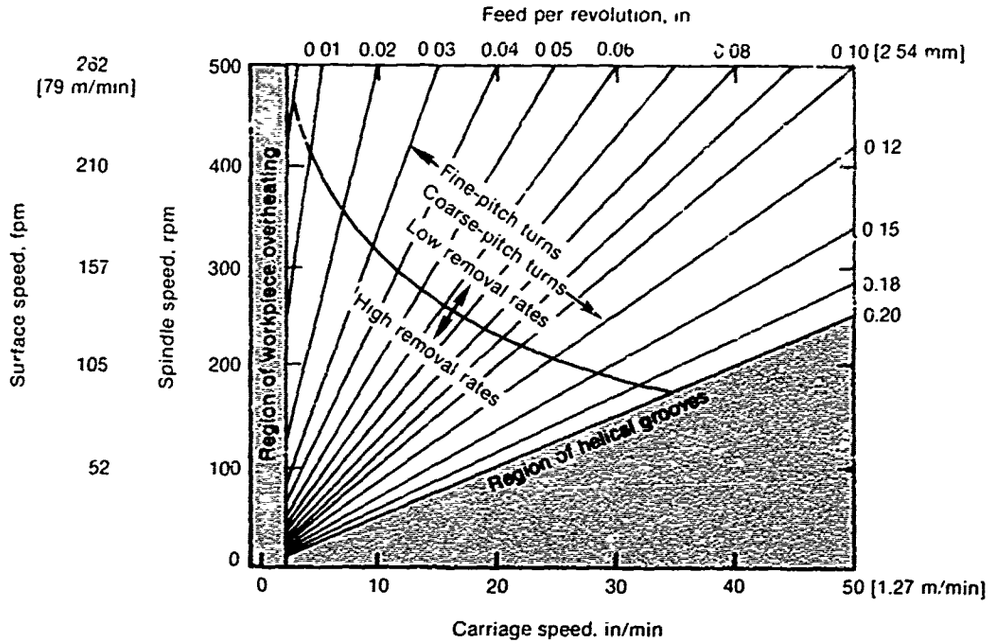


Figure 12.8–4 Interrelationship among some of the factors involved in plasma arc turning. (R. K. Springborn, p. 165)

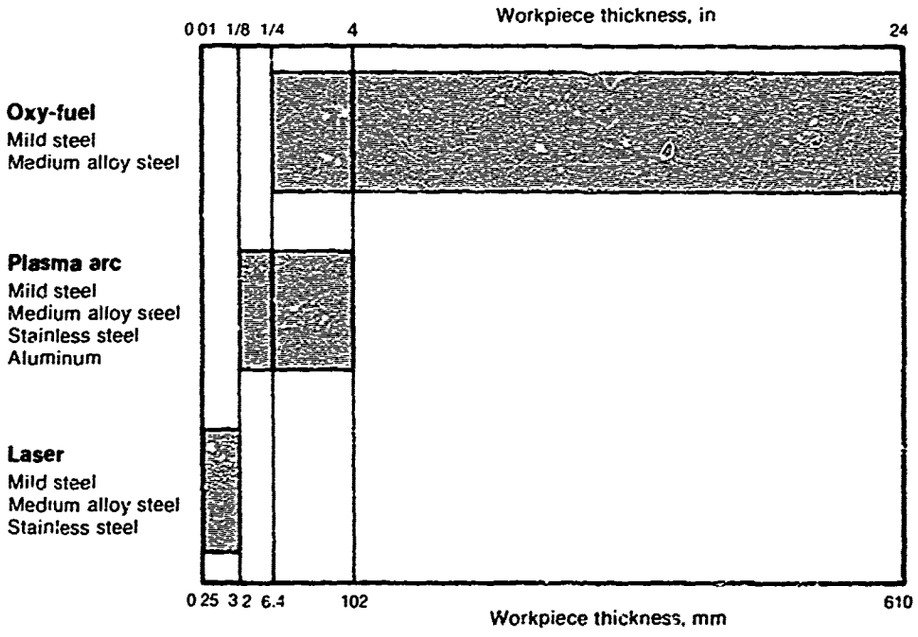


Figure 12.8–5 Comparison of plasma arc, oxy-fuel and laser processes in cutting metals.

SECTION 13

CHEMICAL NONTRADITIONAL MACHINING OPERATIONS

13.1 Chemical Machining—CHM 13–3
13.2 Electropolishing—ELP 13–17
13.3 Photochemical Machining—PCM 13–19
13.4 Thermochemical Machining—TCM or Thermal Energy Method—TEM 13–25

Chemical Machining—CHM 13.1

PROCESS SUMMARY

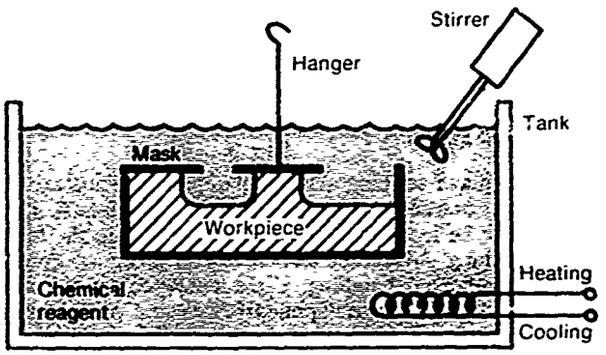


Figure 13.1–1 CHM schematic.

Principles

Chemical machining (CHM) is the controlled dissolution of a workpiece material by contact with a strong chemical reagent (see figure 13.1–1). The thoroughly cleaned workpiece is covered with a strippable, chemically resistant mask. Areas where chemical action is desired are outlined on the workpiece with the use of a template and then stripped of the mask. The workpiece is then submerged in the chemical reagent to remove material simultaneously from all exposed surfaces. The solution should be stirred or the workpiece should be agitated for more effective and more uniform action. Increasing the temperatures will also expedite the action. The machined workpiece is then washed and rinsed, and the remaining mask is removed. Multiple parts can be machined simultaneously in the same tank.

Contour machining is accomplished by successively stripping masks and resubmerging the workpiece in the chemical bath. Etching of the workpiece proceeds radially from the openings in the mask. This results in an undercut as well as a depth of cut. The ratio of distance etched beneath the mask to the distance etched into the workpiece (the etching factor) is typically 1:1 (figure 13.1–6). A controlled rate of immersion or withdrawal from the bath will produce tapered sections. It is preferred that the workpiece be oriented such that the grain is in the direction of the longest cut.

Practical Applications

Nearly all materials can be chemically machined; however, the depth of cut has a practical limit of 0.25 to 0.5 inch (6.4 to 12.7 mm). Large, shallow areas are especially suitable for CHM since removal is uniform and simultaneous. No burrs are produced and no workpiece surface stresses are generated by CHM. Short-run, quick-change, low-cost tooling offers process flexibility. Thin sheets, formed sheets and delicate cuts are particularly suitable for CHM. Sharp radii cannot be produced in the cutting direction.

Workpiece size is limited only by tank dimensions: aluminum wing spars have been chemically machined in 3-by-8-by-50-foot (1 by 2.5 by 15 m) tanks. Surface contours, scratches and waviness will be reproduced as CHM proceeds. Porous castings are poor candidates for CHM, and welds or welded areas are difficult to cut uniformly.

The maximum practical depth of cut varies with the material form as follows:

Sheets and plates:	0.50 inch (12.7 mm)
Forgings and castings:	0.25 inch (6.4 mm)
Extrusions:	0.15 inch (3.8 mm)

See Photochemical Machining, section 13.3, for information on chemical machining of thin or small parts.

Operating Parameters

TABLE 13.1–1 Typical Values for CHM Operating Parameters

Etchant	
types:	Alkalines, acids, proprietary mixtures
concentration:	See table 13.1–3
operating temperature:	70° to 200°F [21° to 93°C]
Maskants:	Rubbers, PVC, polyethylene, neoprene and similar plastics or elastomers (tables 13.1–6 and 13.1–7)
Etching rate:	0.0002 to 0.0025 in/min [0.005 to 0.064 mm/min] typical, 0.001 in/min [0.025 mm/min]
Etch factor:	1:1 usual; up to 1:3 (table 13.1–3) (ratio of undercut to depth of cut)
Metal ion content:	A little is desirable but too much can stop etching. Uncontrolled etching begins at about 75 grams per liter [10 oz/gal].
Tolerance:	Approximately ±10% of cut depth (tables 13.1–8 and 13.1–9, figures 13.1–7 to 13.1–13)

Material Removal Rates and Tolerances

The material removal rate is determined by the solution type, concentration and temperature, all of which are selected to be compatible with the particular metallurgical state of the work material (tables 13.1–3, 13.1–4, and 13.1–5). While the removal rate is low, about 0.001 inch per minute (0.025 mm/min), cutting occurs simultaneously on all exposed surfaces. The depth of cut is controlled by the time of immersion.

Uniformity of removal rates depends upon the chemical and metallurgical uniformity of the workpiece and the uniformity of the solution temperature, concentration and metal ion content (figures 13.1–2 to 13.1–5). Solution or workpiece agitation aids application of the etchant to the

13.1 Chemical Machining—CHM

exposed surface Too violent agitation or fluid directional constraint can lead to uneven cut times or grooving. With good time, temperature and solution control, accuracies up to ±0.0005 inch [±0.0127 mm] can be achieved for shallow depths of cut. Deep cuts yield tolerances up to ±0.005 inch [±0 13 mm] Minimum width of cut or land between cuts should be twice the depth of cut plus the etch factor.

Scribe-and-peel masks can produce ±0.007-inch [±0.18 mm] lateral tolerance per edge Screen masks can produce ±0.003-inch [±0.076 mm] lateral tolerance per edge, and photoresist masks can produce a tolerance of ±0.0005 inch [±0 013 mm]. (See tables 13 1-8 and 13.1-9 and figures 13 1-7 to 13.1-13.)

Surface Technology

The chemical machining process does not introduce stress into the workpiece. The gentle chemical action of removing material by molecule-by-molecule dissolution results in surfaces free from residual stresses

CHM surface roughness values are influenced by the roughness present in the initial workpiece surface and the degree of adherence to the preplanned operating conditions Typically, very smooth surfaces (32 microinches R_a [0.8 μm] or less) are slightly roughened, while rough surfaces (125 microinches R_a [3.2 μm] or more) are slightly smoothed; see figure 13.1-14 and table 13.1-10 Surface roughness values increase as the metal ion concentration increases in the etchant.

Hydrogen embrittlement and intergranular attack can occur and can have detrimental effects on material properties unless post-treatment corrective action is taken.

Equipment and Tooling

Equipment runs from small bench-top devices to outdoor tanks, 6 by 12 by 60 feet [1 8 by 3.7 by 18 m] Both submerged and spray etching are used. Automation of sequence of wash and etchant immersion is commonplace. Agitation by air or by mechanical motion is frequently built into the material handling fixtures. Excessive air agitation can lead to excessive fuming. Multiple part handling racks are commonly used.

Masking, mask scribing and templates for scribing are of many types and shapes (see tables 13.1-6 and 13 1-7). The mask must be inert to the chemical reagent and the heat during etching Adherence and ease of stripping are necessary to withstand handling. Dip-cut-and-peel masks are common, and silk-screen-applied resists and photoresists are used for higher production rates. Lateral accuracy, figures 13 1-9 and 13.1-10, is affected by type of mask:

Cut-and-peel mask:	±0.007 inch [±0.18 mm]
Screen resists:	±0 003 inch [±0.076 mm]
Photoresists:	±0.0005 inch [±0 013 mm]

Machining Characteristics

Chemically resistant floors, plumbing, ventilation and solution controls are required. Special environmental and safety precautions are required to meet local limitations Automatic monitoring of the chemicals is commonplace. Chemical etchants, by their very nature, are very corrosive. Extreme care in handling is required to avoid spillage and splashing. Vigilance must be maintained at all times. The fumes are corrosive and may be toxic with health risks and risks to nearby equipment or building structures, see table 13.1-11.

SELECTED DATA

There are several valid techniques for selecting operating parameters for CHM. The steps in table 13.1-2 are recommended as one logical sequence. Supporting data come from the other figures and tables.

TABLE 13.1-2 Steps To Select CHM Operating Parameters

ITEM	DATA
1. Workpiece material: type heat treatment grain size metallurgical state rolling direction	Engineering drawings
2. Select compatible etchant: type concentration temperature	Tables 13.1-3, 13.1-4 and 13.1-5; figures 13.1-2 to 13.1-5
3. Estimate etching rate:	Tables 13.1-1, 13.1-3, 13.1-4 and 13.1-12; figures 13.1-2 to 13.1-5
4. Calculate time of immersion from depth of cut:	Drawing dimension divided by estimated etching rate
5. Run test specimen to check estimates and establish final value for operating parameters:	Laboratory tests on specimen with exactly same finish and metallurgical state as the production workpiece
6 Check surface roughness attained:	Specimens from item 5 using final operating parameters
7 Quality control:	Deviations from surface roughness or etching rate during a production run signal the need for corrective changes in the etching bath conditions
8. Tooling: maskant type	Tables 13.1-6 and 13.1-7
template design and undercut allowances	Table 13.1-3; figures 13.1-6, 13.1-8, 13.1-9 and 13.1-10
9. Safety precautions: handling ventilation effluents	Local safety practices, OSHA guidelines, EPA guidelines

TABLE 13.1–3 Etchant Characteristics and General Applications

METAL THAT ETCHANT WILL ATTACK	ETCHANT	ETCHANT CONCENTRATION	OPERATING TEMPERATURE		ETCH RATE WITH FRESH SOLUTION		ETCH FACTOR*
			°F	°C	in/min	mm/min	
Alfenol	$FeCl_3$	42° Be'†	120	49	—	—	—
	HNO_3:HCl H_2O	1:1:2	100 to 120	38 to 49	—	—	—
Aluminum alloys	$FeCl_3$	12 to 18°	120	49	0 001 +	0.025	1.5:1 to 2:1
	HCl:HNO_3 H_2O	10:1:9	120	49	0.001 to 0.002	0.025 to 0.050	2:1 (variable)
Cold rolled steels	$FeCl_3$	42° Be	120	49	0.001	0.025	2:1
	HNO_3	10 to 15% vol.)	120	49	0.001	0.025	1.5 to 2:1
Copper and its alloys	$FeCl_3$	42° Be'	120	49	0.002	0.050	2.5 to 3:1
	$(NH_4)_2S_2O_8$	2.2 lb/gal [263g/L] H_2O	90 to 120	32 to 49	0.001	0.025	2 to 3:1
	Chromic acid	commercially available	120	49	0 0015	0.038	2 to 3:1
	$CuCl_2$	35° Be' (regenerated)	130	54	0 00055	0.014	2.5 to 3:1
Germanium	HF or HF:HNO_3	various	—	—	—	—	—
Glass	HF or HF:HNO_3	various	—	—	—	—	—
Gold	HCl:HNO_3	3:1	90 to 100	32 to 38	0.001 to 0.002	0.025 to 0.050	—
Hardened tool steel	HNO_3	10 to 15% (vol)	100 to 120	38 to 49	0 0005 to 0.001	0.013 to 0.025	1:1 to 2:1
Inconel	$FeCl_3$	42° Be'	130	54	—	—	—
Inconel alloy X	$FeCl_3$	42° Be'	130	54	—	—	—
Kovar	Chromic acid	commercially available	120	49	0.001	0.025	2 to 2.5:1
	$FeCl_3$	40° Be'	120	49	0.001	0.025	2.1
Lead	$FeCl_3$	42° Be'	130	54	—	—	—
Magnesium	HNO_3	12 to 15% (vol.)	90 to 120	32 to 49	0 001 to 0 002	0.025 to 0.050	—
Moly permalloy	$FeCl_3$	42° Be'	130	54	—	—	—
Molybdenum	H_2SO_4:HNO_3 H_2O	1:1:1 to 5	130	54	0.001 at 130°F varies with temp.	0.025 at 54°C varies with temp.	—
	HNO_3:HCl.H_2O	1:1:1 to 2	—	—	—	—	—
Nickel	$FeCl_3$	42° Be'	120	49	0.0005 to 0.001	0.013 to 0.025	1:1 to 3:1
Nickel-iron alloys	$FeCl_3$	42° Be'	120	49	0.0005 to 0.001	0.013 to 0.025	1:1 to 3:1
Nickel-silver alloys	$FeCl_3$	42° Be'	130	54	—	—	—
	Chromic acid	commercially available	120	49	—	—	—
	$(NH_4)_2S_2O_8$	2 2 lb/gal [263g/L] H_2O	90 to 120	32 to 49	—	—	—
Phosphor-bronze	$FeCl_3$	42° Be'	cold (80)	27	0.0005	0.013	2.1
	Chromic acid	commercially available	cold (90)	27	0.0005	0.013	2:1
	$(NH_4)_2S_2O_8$	2.2 lb/gal [263g/L] H_2O	cold (80)	27	0.0003	0.008	2:1
Silicon	HNO_3:HF:H_2O	various	100 to 120	38 to 49	slow	slow	—
Silicon steel	$FeCl_3$	42° Be'	130	54	0 001	0.025	1.5 to 2:1
Silver	HNO_3:H_2O	50 to 90% (vol.)	100 to 120	38 to 49	0.0005 to 0.001	0.013 to 0.025	—
	$FeNO_3$	36° Be'	120	49	0.0008	0.020	—
Stainless steel	$FeCl_3$	42° Be'	130	54	0.0008	0.020	1.5 to 2:1
Tin	$FeCl_3$	42° Be'	130	54	—	—	—
Titanium	HF	10 to 50% (vol.)	100 to 120	38 to 49	—	—	—
	HF:HNO_3:H_2O	various	100 to 120	38 to 49	—	—	—
	NH_4HF_2:HCl:H_2O	various	100 to 120	38 to 49	—	—	—
Zinc	HNO_3	10 to 15% (vol.)	100 to 120	38 to 49	0.001	0.025	—

*The ratio of depth of undercut to depth of cut.

†Baume' specific gravity scale (Be').

TABLE 13.1–4 Comparison of Data and Characteristics of Systems for Chemical Milling Titanium, Steel, Aluminum, and Nickel- and Cobalt-Base Alloys

METAL	PRINCIPAL ETCHANT	ETCH RATE		OPTIMUM ETCH DEPTH		ETCHANT TEMPERATURE		AVERAGE SURFACE ROUGHNESS, R_a	
		in/min	mm/min	in	mm	°F	°C	μin	μm
Titanium alloys	Hydrofluoric acid	0.0006 to 0.0012	0.015 to 0.030	0.125	3.2	115 ±5	46 ±2.7	16 to 100	0.4 to 2.5
Steels	Hydrochloric acid-nitric acid	0.0006 to 0.0012	0.015 to 0.030	0.125	3.2	145 ±5	63 ±2.7	30 to 120	0.8 to 3.2
Aluminum alloys	Sodium hydroxide	0.0008 to 0.0012	0.020 to 0.030	0.125	3.2	195 ±5	90 ±2.7	80 to 120	2.0 to 3.2
Nickel- and cobalt-base alloys	Nitric acid-hydrochloric acid-ferric chloride	0.0004 to 0.0015	0.010 to 0.038	0.125	3.2	140 ±5	60 ±2.7	40 to 150	1.0 to 3.8

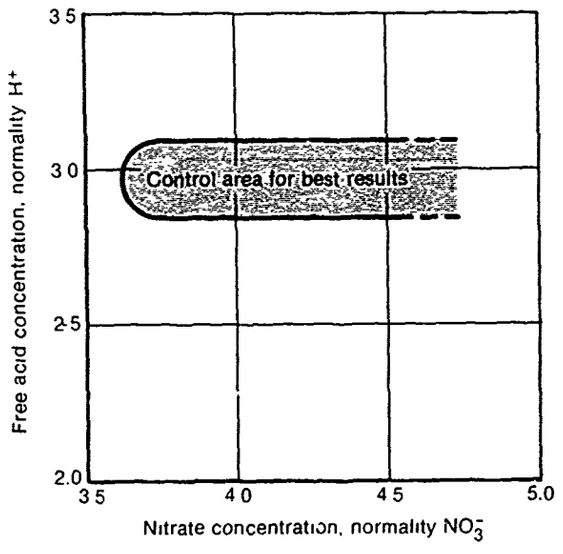


Figure 13.1–2 Suitable working ranges for the free acid and nitrate concentrations of an aqua-regia-type etchant for 18/8 stainless steels. (W. T. Harris, *Chemical milling,* Oxford. Clarendon Press, 1976, p 239)

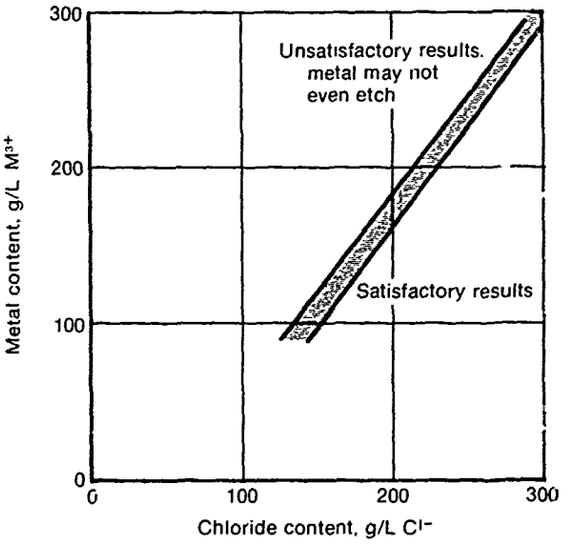


Figure 13.1–3 Relationship between metal and chloride content for an aqua-regia-type etchant (W. T. Harris, p. 238)

13.1 Chemical Machining—CHM

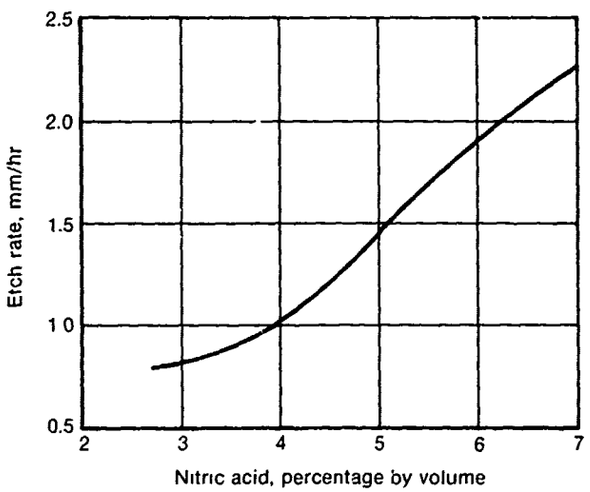


Figure 13.1–4 The effect on etch rate of increasing the nitric acid concentration in an etchant containing 25 percent sulfuric acid at 70°C (158°F). (W T Harris, p. 234)

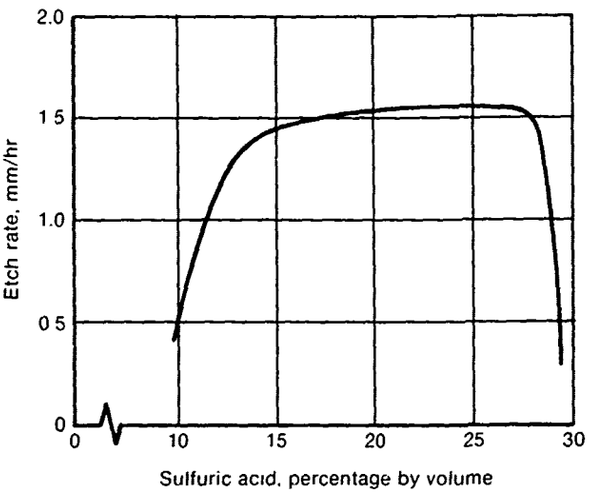


Figure 13.1–5 The effect on etch rate of increasing the sulfuric acid concentration in an etchant containing 5 percent nitric acid at 70°C (158°F). (W. T. Harris, p. 234)

TABLE 13.1–5 Etchants for Steel, Nickel and Cobalt Alloys

METAL ALLOY	H^+(N)	NO_3^-(N)	PO^-(N)	F^-(N)	METAL ION g/L
Mild steel	2.0 to 3.5	0.2 to 4.1	1.5 to 3.0		100 to 250
Stainless steel	2.0 to 3.5	0.2 to 4.1	1.5 to 3.0		100 to 250
Nickel alloys	2.0 to 3 5	0.2 to 4.1	1.5 to 3.0		100 to 250
Cobalt alloys	2.0 to 5.5	0.2 to 2.0	0 to 3.0	0.5 to 1.0	125 to 250

SOURCE: W. T. Harris, p. 235.

TABLE 13.1-6 Typical Maskants for Various Metals

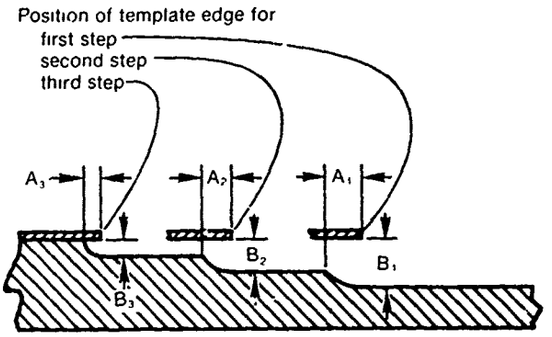
METAL	ETCHANT	TEMPERATURE °C	MASKANTS
Aluminum	Alkaline	91	Acrylonitrile rubber, butyl rubber, neoprene rubber
Ferrous metals	Acid	54	Polyvinyl chloride, polyethylene, butyl rubber
Magnesium	Acid	<38	Polymers
Titanium	Acid	21 to 35	Translucent chlorinated polymers
Titanium	Acid	54	Vinyl polymers, elastomers
Beryllium	Acid	21 to 54	Vinyl, neoprene, butyl-based materials
Nickel	Acid	45 to 50	Neoprene

TABLE 13.1-7 Properties of Maskant Materials Widely Used in Chemical Milling

PROPERTY	MASKANT MATERIAL				
	Exposure to Oxidizing Acids		Exposure to Acids or Alkalis		
	Polyvinyl chloride	Polyethylene	Butyl rubber	Acrylonitrile rubber	Neoprene rubber
Ease of manufacture	Good	Good	Fair	Fair	Good
Shelf life, months	6 to 12	6 to 12	4 to 6	3 to 6	6 to 8
Solids, %	25 to 55	60 to 100	20 to 25	15 to 25	25 to 35
Ease of application:					
dipping	Good to fair	Poor to fair	Good	Good	Good
flow coating	Good to fair	Poor to fair	Good	Good	Good
air spraying	Good	Good	Poor	Poor	Fair
Type of cure	Air or heat	Heat	Heat	Air or heat	Air or heat
Tensile strength, MN/m^2					
air-dried (24 hr)	—	—	—	7 max.	14 max.
heat cured	7 to 17.5	6 to 11	6 to 11	11 to 17.5	11 to 21
Resistance to etchant:					
deterioration	Good to excellent	Very good	Very good	Very good	Very good
permeability	Fair to good	Very good	Excellent	Very good	Very good
Heat limit °F*	160	140	300	250	200

*Maximum useful temperature for intermittent exposure—also curing temperature.

13.1 Chemical Machining—CHM



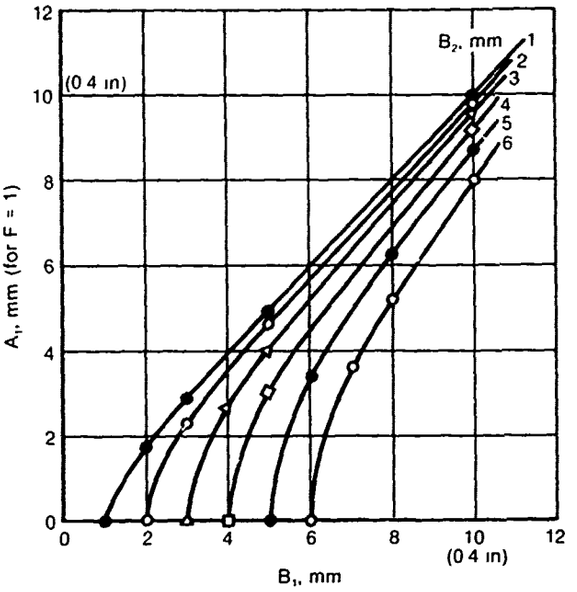


Figure 13.1–6 Undercut allowance, A, for step chemical milling. Allowance is for adjacent steps B_1 and B_2 with various step depths. Note: Etch factor for CHM is ratio of undercut to depth of cut or F = A ÷ B. Caution: In photochemical machining, the factor is defined as the inverse ratio, B ÷ A. (W. T. Harris, p 268–69)

TABLE 13.1–8 Typical Surface Dimensional Tolerances

WORK MATERIAL	TOLERANCE, in					TOLERANCE, mm				
	Workpiece Thickness, in					Workpiece Thickness, mm				
	0.002	0.005	0.010	0.020	0.030	0.05	0.13	0.25	0.50	0.75
Aluminum alloys	±0.0005	±0.0012	±0.0025	±0.005	±0.008	±0.013	±0.030	±0.063	±0.13	±0.20
Copper and copper alloys	±0.0004	±0.001	±0.002	±0.004	±0.006	±0.010	±0.025	±0.050	±0.10	±0.15
Nickel	±0.0005	±0.0012	±0.0025	±0.005	±0.008	±0.013	±0.030	±0.063	±0.13	±0.20
Steel alloys	±0.0004	±0.001	±0.002	±0.004	±0.006	±0.010	±0.025	±0.050	±0.10	±0.15
Stainless steel	±0.0005	±0.0012	±0.0025	±0.005	±0.008	±0.013	±0.030	±0.063	±0.13	±0.20

SOURCE: Chemcut Corporation, State College, PA.

TABLE 13.1–9 Tolerance on Depth of Cut

MATERIAL	TOLERANCE, in				TOLERANCE, mm			
	Depth of cut, in				Depth of cut, mm			
	0–0.050	0.051–0.100	0.101–0.250	0.251–0.500	0–1.25	1.25–2.50	2.5–6.4	6.4–12.7
General	0.002	0.003	0.004	0.006	0.05	0.075	0.10	0.15
Aluminum and magnesium alloys	0.001	0.0015	0.002	0.003	0.025	0.038	0.05	0.075
Stainless steels, ferrous and nickel alloys	0.002	0.003	0.004	0.006	0.05	0.075	0.10	0.15
Titanium and beryllium alloys	0 003	0.004	0.006	0.010	0.075	0.10	0.15	0.25

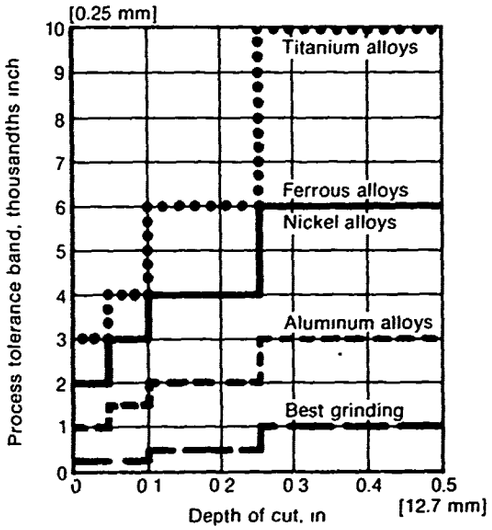


Figure 13.1–7 CHM depth-of-cut tolerance for sheet materials.

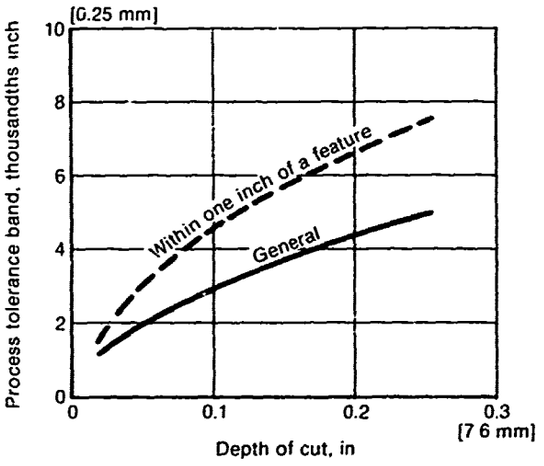


Figure 13.1–8 Depth-of-cut tolerance capability of CHM.

13.1 Chemical Machining—CHM

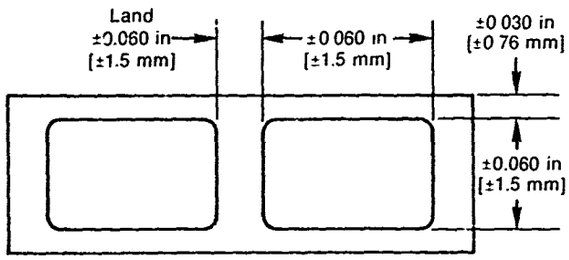


Figure 13.1–9 Nominal lateral tolerance.

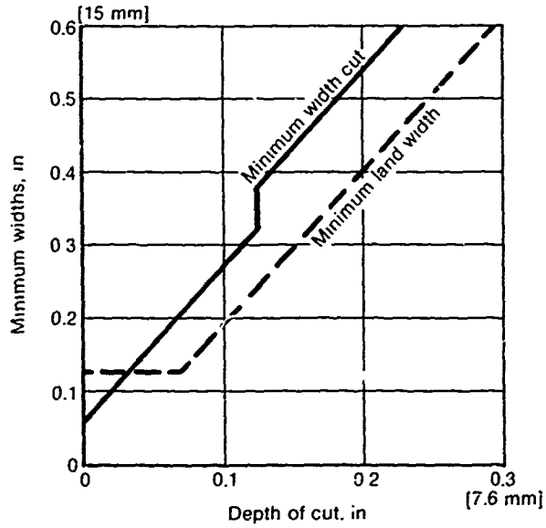


Figure 13.1–10 Recommended minimum widths of cut and land for CHM.

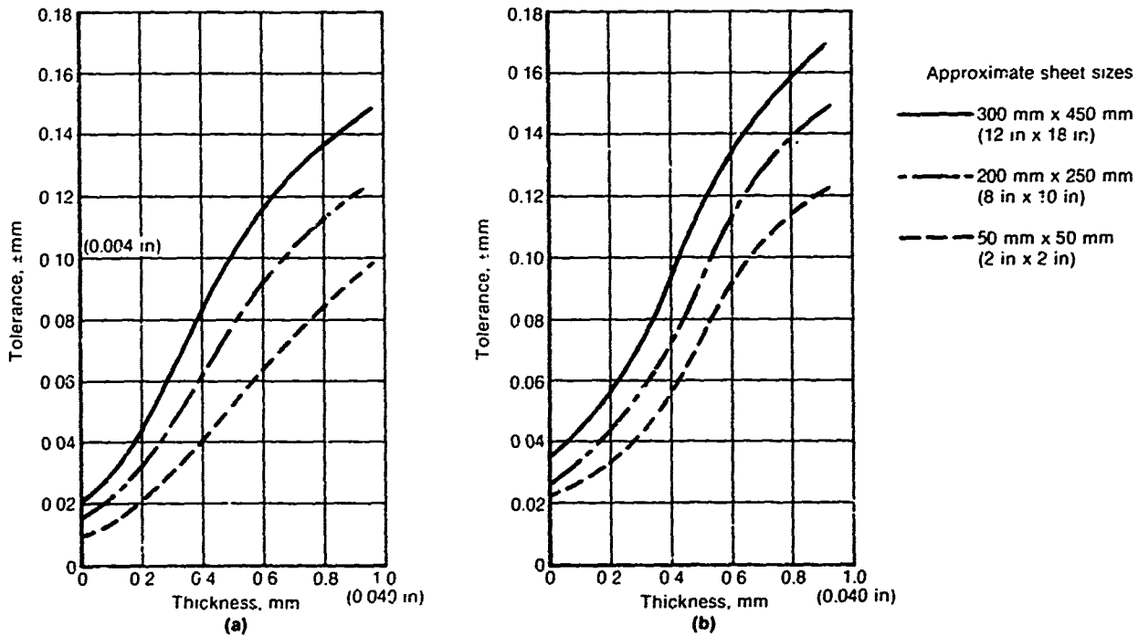


Figure 13.1–11 Practical tolerances on etched dimensions, for a range of flat sheet sizes and material thickness. (a) For prototype and short runs; (b) for production runs. (W. T. Harris, p. 192)

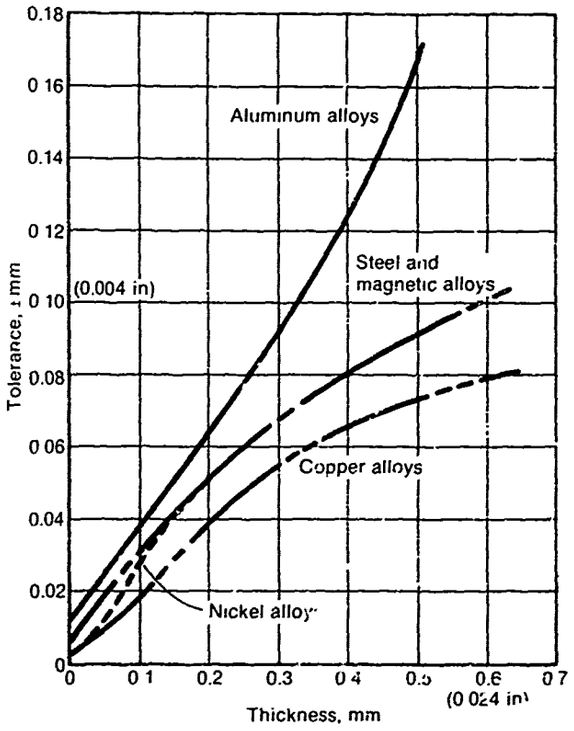
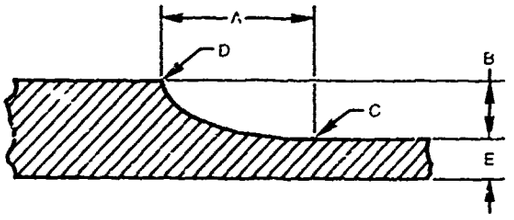


Figure 13.1–12 Normally attained dimensional tolerances for a range of materials. (W. T. Harris, p. 193)



A — maximum transition zone
B — depth of cut
C — point where normal thickness is reached
D — milling cut edge
E — web thickness

Materials	Maximum Transition Zone
Aluminum alloys	4 x depth of cut
Magnesium alloys	6 x depth of cut
Ferrous alloys	10 x depth of cut
Nickel and Cobalt alloys	10 x depth of cut
Titanium alloys	10 x depth of cut or 0.5 inch (12.7 mm) (whichever is greater)

Figure 13.1–13 Transition zones of CHM.

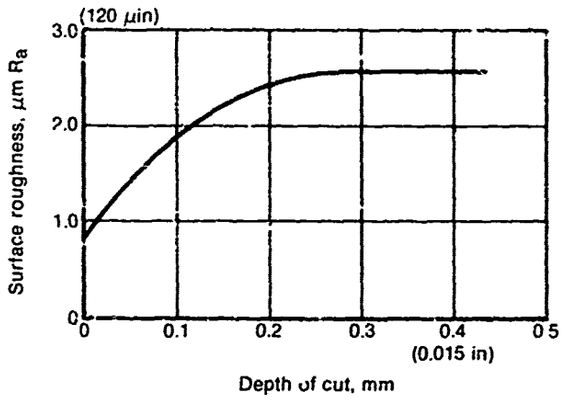


Figure 13.1–14 The relationship between surface finish and depth of cut for chemical milling 7075 aluminum sheet. (W. T. Harris, p. 112)

13.1 Chemical Machining—CHM

TABLE 13.1–10 Surface Roughness Achieved by Chemical Milling

MATERIAL	FORM	SURFACE ROUGHNESS AFTER 0.25 to 0.40 mm (0.010 to 0.015 in) REMOVED	
		μm R_a	μin R_a
Aluminum alloys	Sheet	2.0 to 3.8	80 to 150
	Casting	3.8 to 7.6	150 to 300
	Forging	2.5 to 6.4	100 to 250
Magnesium alloys	Casting	0.75 to 1.4	30 to 55
	Forging		
Steel alloys	Sheet	0.75 to 1.5	30 to 60
	Forging		
Nickel alloys	Sheet	0.75 to 1.0	30 to 40
Titanium alloys	Sheet	0.2 to 0.8	8 to 32
	Casting	0.75 to 1.5	30 to 60
	Forging	0.38 to 1.0	15 to 40
Tungsten	Bar	0.5 to 1.0	20 to 40
Beryllium	Bar	3.8 to 6.4	150 to 250
Tantalum	Sheet	0.25 to 0.5	10 to 20
Columbium	Bar	1.0 to 1.5	40 to 60
Niobium (Columbium)	Sheet	1.0 to 1.5	40 to 60
Molybdenum	Sheet	1.5 to 3.3	60 to 130

SOURCE: W T Harris, p. 114.

TABLE 13.1–11 Summary of Health Risk Arising from the Commonly Used Etchants

MATERIAL BEING ETCHED	ETCHANT(S)	ETCHANT RISK(S)	FUME RISK(S)
Aluminum alloys	Sodium hydroxide	Splashes on to skin, mouth, or eyes	Fume not dangerous but hydrogen gas is explosive
Magnesium alloys	Sulphuric acid	Splashes on to skin, mouth, or eyes. Additions may cause spattering	Corrosive acidic fume. Hydrogen gas is explosive
Steel/nickel alloys	Hydrochloric, nitric, sulphuric and phosphoric acids	Highly corrosive splashes on to skin, mouth, or eyes	Corrosive and suffocating fume is also toxic
Titanium alloys	Hydrofluoric acid with nitric or chromic acid	Highly corrosive splashes on to skin, mouth, or eyes. Hydrofluoric acid is particularly dangerous	Corrosive and suffocating fume is also toxic
Copper alloys	Ferric chloride	Corrosive splashes on to skin, mouth, or eyes	Corrosive and suffocating fume

SOURCE: W. T. Harris, p. 107

TABLE 13.1-12 Consolidated Chemical Machining Data

MATERIAL TYPE	ETCHANT	ETCHANT CONCENTRATION	OPERATING TEMPERATURE		ETCH RATE		MASKANT	ETCH FACTOR*	ROUTINE DEPTH OF CUT TOLERANCE		SURFACE ROUGHNESS	
			°F	°C	in x 10^{-3}/min	mm/min			± in	± mm	μin R_a	μm R_a
Aluminum and aluminum alloys	$FeCl_3$ NaOH	11–15°Be'† 150 g/L	120 120	49 49	0.5–1.0 0.8–1.2	0.013–0.025 0.020–0.030	Polymers Neoprene	— 1.5–20	— 0.002	— 0.050	— 90–125	— 2.3–3.2
Beryllium Brass/Bronze	NH_4HF_2 $FeCl_3$	15% vol. 32°Be'	80 120	27 49	0.4–0.6 1.0	0.010–0.015 0.025	Neoprene —	— —	0.001–0.003 0.001	0.025–0.076 0.025	125 32	3.2 0.8
Chromium	$K_3Fe(CN)$ HCl	— 10–50% vol.	— —	— —	— 0.5	— 0.013	— —	— —	— —	— —	— —	— —
Cobalt alloys	HNO_3:HCl:$FeCl_3$	—	140	60	0.4–1.5	0.010–0.038	—	—	—	—	40–150	1.0–3.8
Columbium	HNO_3:HF:H_2O	1:1:4	Ambient	Ambient	0.5–1.0	0.013–0.025	—	—	—	—	—	—
Copper	$FeCl_3$ $CuCl_2$	32°Be' 42°Be'	120 120	49 49	2.0 1.2	0.050 0.030	— —	2.5–3.0 2.5–3.0	0.003 0.003	0.076 0.076	— —	— —
Gold	$HCl:HNO_3$ $KI:I_2:H_2O$	3:1 75 lb:25 lb: 15 gal	100 100	38 38	1.0–2.0 1.0–2.0	0.025–0.050 0.025–0.050	— —	1.0 1.0	— —	— —	— —	— —
Inconel	$FeCl_3$ $HCl:HNO_3$	42°Be' 42°Be'	130 130	54 54	0.5–1.5 0.5–1.5	0.013–0.038 0.013–0.038	Polyethylene Polyethylene	— —	— —	— —	40–150 40–150	1.0–3.8 1.0–3.8
Indium oxide Invar	$HCl:HNO_3$ $FeCl_3$	50:5% vol. 42°Be'	120 130	49 54	0.5–1.0 —	0.013–0.025 —	Polymers —	— —	— —	— —	— —	— —
Kovar Lead	$FeCl_3$ $FeCl_3$	42°Be' 42°Be'	130 130	54 54	0.75 1.0	0.019 0.025	Polymers —	1.0–2.0 1.0	— —	— —	— —	— —
Magnesium	HNO_3	12–15% vol.	90 to 120	32 to 49	1.0–2.0	0.025–0.050	Polymers	1.0	0.002	0.051	50	1.3
Molybdenum	H_2SO_4:HNO_3:H_2O	1:1:1	130	54	1.0	0.025	—	1.0	—	—	—	—
Nickel, Nimonic	$FeCl_3$ $FeCl_3$:HNO_3:HCl	42°Be' —	120 120	49 49	0.5–1.5 0.5–1.5	0.013–0.038 0.013–0.038	Polyethylene Polyethylene	1.0–3.0 1.0–3.0	0.002 0.002	0.051 0.051	40–150 40–150	1.0–3.8 1.0–3.8

*The ratio of depth of undercut to depth of cut.

† Baume specific gravity scale (Be').

TABLE 13.1-12—Continued

MATERIAL TYPE	ETCHANT	ETCHANT CONCENTRATION	OPERATING TEMPERATURE		ETCH RATE		MASKANT	ETCH FACTOR*	ROUTINE DEPTH OF CUT TOLERANCE		SURFACE ROUGHNESS	
			°F	°C	in x 10^{-3}/min	mm/min			± in	± mm	μin R_a	μm R_a
Phosphor-bronze	$FeCl_3$	42°Be'	80	26	0.5	0.013	—	2.0	—	—	—	—
Silicon	HF	—	—	—	—	—	—	—	—	—	—	—
	$HF:HNO_3$	—	—	—	—	—	—	—	—	—	—	—
Silver	$HNO_3:H_2O$	50–90% vol.	120	49	0.5–1.0	0.013–0.025	—	1.0	—	—	—	—
Stainless steel austenitic	$FeCl_3$ (or HCl: HNO_3)	42°Be'	130	54	0.8–5.0	0.020–0.130	Polyvinyl chloride	1.5–2.0	0.004	0.1	63	1.6
martensitic	$FeCl_3$ (or HCl. HNO_3)	42°Be'	130	54	0.25	0.006	Polyvinyl chloride	—	0.004	0.1	125	3.2
Mild steel	$FeCl_3$ (or HCl: HNO_3)	32°Be'	120	49	1.0	0.025	Polyvinyl chloride	2.0	0.002	0.05	63	1.6
Silicon steel	$FeCl_3$ (or HCl: HNO_3)	32°Be'	130	54	1.0	0.025	Polyvinyl chloride	1.5–2.0	0.002	0.05	63	1.6
Tool steel	$FeCl_3$ (or HCl: HNO_3)	32°Be'	130	54	1.0	0.025	Polyvinyl chloride	—	—	—	—	—
Tantalum	$HF:HNO_3$	10:5	120	49	0.2–0.5	0.005–0.013	—	—	—	—	—	—
Tin	$FeCl_3$ (or HCL: HNO_3)	32°Be'	130	54	1.0	0.025	—	—	—	—	—	—
Titanium	HF	10–50% vol.	120	49	0.6–1.5	0.015–0.038	Vinyl polymers	1.0	0.002–0.0035	0.05–0.009	15–100	0.4–2.5
	$HF:HNO_3$ (or HF: CrO_3)	—	115 ± 10	46 ± 5.6	0.6–1.5	0.015–0.038	Vinyl polymers	1.0	0.002–0.005	0.05–0.13	15–100	0.4–2.5
Tungsten	$K_3Fe(CN)_6$: NaOH	20% wt.: 2–3% wt.	70 to 130	21 to 54	—	—	—	—	—	—	—	—
	$HF:HNO_3$	30–70% vol	80	27	—	—	—	—	—	—	—	—
Uranium	$FeCl_3$	1,400 g/L	75	24	0.04	0.001	—	—	—	—	—	—
Zinc	HNO_3	10–15% vol	120	49	1.0	0.025	—	—	—	—	—	—
Zirconium	HNO_3: H_2SiF_6: NH_4HF_2	4:2:1	90	32	1.8	0.046	—	—	—	—	—	—

PROCESS SUMMARY

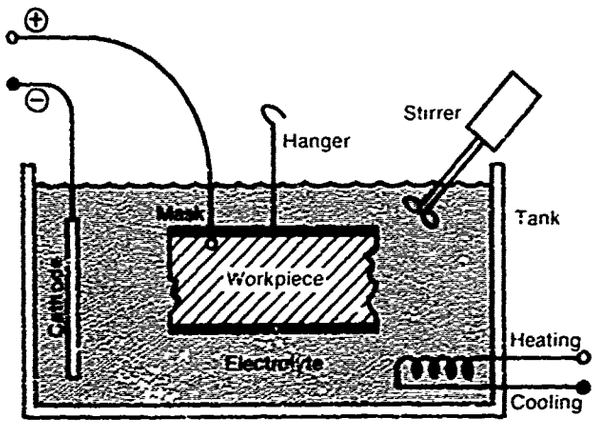


Figure 13.2–1 ELP schematic.

Principles

Electropolishing (ELP) is a specialized form of chemical machining which uses an electrical deplating action to enhance the chemical action (see figure 13.2–1). The chemical action from the concentrated heavy acids does most of the work, while the electrical action smooths or polishes the irregularities. A metal cathode is connected to a low-voltage, low-ampere, direct-current power source and is installed in the chemical bath near the workpiece. Usually, the cathode is not shaped or conformed to the surface being polished. The cutting action takes place over the entire exposed surface; therefore, a good flow of heated, fresh chemicals is needed in the cutting area to secure uniform finishes. The cutting action will concentrate first on burrs, fins and sharp corners. Masking, similar to that used with CHM, prevents cutting in unwanted areas. The proper choice of an electrolyte can enhance the "throwing power" of the direct current to polish recesses and speed the cutting action. Almost any electrically conductive material can be polished by this process.

Practical Applications

Electropolishing's gentle removal action produces a workpiece surface of high quality and introduces no stresses. It is frequently used as a finishing process for appearance or smoothness, or for applications where the absence of process-induced residual stresses in the workpiece is desirable. Antifriction surfaces can be more consistent, and corrosion resistance can be improved. The pure or unaltered mechanical properties of a workpiece material remain after finishing with ELP.

On some alloys, for example, 17-4 PH, electropolishing is successful in removing tightly adhering scale after forging and as a preliminary process to passivation

Operating Parameters

TABLE 13.2–1 Typical Values for ELP Operating Parameters

Bath	
types:	Acid mixtures, sodium hydroxide and proprietary solutions (see table 13.2–2)
temperature:	70° to 200°F [21° to 93°C]
Current density:	50 to several hundred amperes per square foot [0.05 to several times 0.1 A/cm²]

Material Removal Rates and Tolerances

The removal rates are very slow, on the order of 0.0005 to 0.0015 inch per minute [0.013 to 0.038 mm/min]; however, it usually requires only a few minutes exposure to achieve the desired surface improvement. The current density in the electrolyte concentrates around the surface asperities; consequently, erosion of the asperities takes place at a faster rate than erosion in the declivities. The surface, therefore, can be smoothed without considerable material removal.

Surface Technology

Surface roughness depends upon the roughness of the initial surface and the time of immersion. The typical roughness values range from 4 to 32 microinches R_a [0.1 to 0.8 µm], with 1 to 2 microinches R_a [0.025 to 0.05 µm] achievable. When nonconducting masks are used, an additional depth of cutting is experienced adjacent to the mask. ELP produces a surface that is free from residual stress and essentially unblemished. The uniformity of surface conditions also is enhanced.

Equipment and Tools

Commercial plating or chemical machining equipment can be readily adapted for ELP use.

Machining Characteristics

Caution in handling the strong chemicals is essential. Suitable venting for fumes and environmentally proper disposal of spent fluids are necessary.

13.2 Electropolishing—ELP

SELECTED DATA

TABLE 13.2-2 Electropolishing Parameters for High Strength Alloys

MATERIAL	TYPE BATH	CURRENT DENSITY		BATH TEMPERATURE	
		A/ft²	A/cm²	°F	°C
300 series stainless steel	Phosphoric acid	100	0.10	122	50
300 & 400 series stainless steel	Phosphoric-Sulfuric acid	30	0.03	80 to 280	27 to 138
300 & 400 series stainless steel	Phosphoric-Chromic acid	100 to 1,000	0.10 to 1.0	80 to 175	27 to 80
Waspaloy and Nimonic 80	Phosphoric-Sulfuric acid	860	0.9	82 to 90	28 to 32
S-816	Phosphoric-Sulfuric-Chromic acid	500	0.5	200 to 260	93 to 126
AMS 5615	Phosphoric-Sulfuric acid	400	0.4	200	93
Beryllium (rapid agitation needed)	Perchloric-Ethanol-Butyl Cellosolve	700 to 840	0.75 to 0.90	<95	<35
	Phosphoric-Sulfuric-Glycerol-Ethanol	1,900 to 3,700	2.0 to 4.0	68	20
Titanium	Chromic-Hydrofluoric acid	200 to 500	0.2 to 0.5	60 to 70	16 to 21
	10% Sulfamic acid in formamide (no water)	6.5 to 8.1	0.007 to 0.0087	77	25
	Phosphoric-Hydrofluoric-Metnanol	500 to 1,000	0.5 to 1.1	60 to 80	16 to 27
Tungsten	Sodium Hydroxide	30 to 50	0.03 to 0.05	68	20
Rene 41	Phosphoric-Sulfuric acid	400	0.4	70	21
Molybdenum	Ortho Phosphoric acid-Sulfuric acid-Molybdic Anhydride-Water	3.9 to 5 8	0.004 to 0.006	160	71

PROCESS SUMMARY

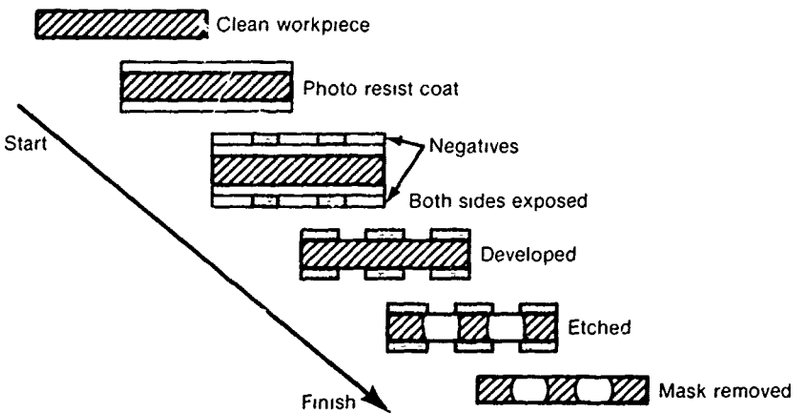
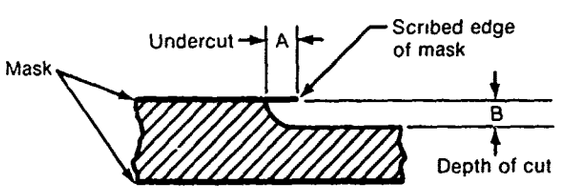


Figure 13.3-1 PCM schematic.

Principles

Photochemical machining (PCM) is a variation of CHM where the chemically resistant mask is applied to the workpiece by a photographic technique (see figure 13.3-1). A photographic negative, often a reduced image of an oversize master print, is applied to the workpiece and developed. Precise registry of duplicate negatives on each side of the sheet is essential for accurately blanked parts. Immersion or spray etching is used to remove the exposed material The chemicals used must be active on the workpiece, but inactive against the photoresist mask There will be some undercutting behind the mask, however, which limits the use of PCM to thin materials—up to 3/32 inch [2.4 mm] (see figure 13.3-2).



$$\text{Etch factor} = \frac{\text{Depth of cut}}{\text{Undercut}} = \frac{B}{A}$$

Figure 13.3-2 Etch factor in photochemical machining. (Note: Inverse of that used in chemical machining.)

Practical Applications

Photochemical blanking is burr free and is capable of producing intricate designs. A wide range of materials can be etched; brittle materials can be "blanked" since there is no mechanical strain. Small lot sizes can be produced at lower cost than with conventional mechanical presses, and there is a short cycle time from design to finished part. Cost of tooling is low and design changes can be quickly effected. Flat, thin-gauge, small complex parts ranging in thickness from 0.001 to 0.020 inch [0.025 to 0.50 mm] are most easily produced by PCM. Table 13.3-1 contains a list of work materials that can be processed with PCM.

Operating Parameters

Operating parameters and typical values are similar to those for CHM; however, some metals that can be chemically machined do not easily respond to PCM because the photoresist masks are more fragile (for example, Waspaloy and Rene 41).

Material Removal Rates and Tolerances

Cutting rates range from 0.0004 to 0.0020 inch per minute [0.01 to 0.05 mm/min], depending on the material and its metallurgical state (see tables in section 13.1). Tolerance increases with material thickness, as shown in tables 13.3-2 to 13.3-6 and figure 13.3-3. On surface dimensions, the typical tolerance is ±15 percent of the material thickness; however, any one dimension can be held to ±10 percent when other dimensions are allowed to vary by ±25 percent of the material thickness.

13.3 Photochemical Machining—PCM

TABLE 13.3-1 Materials that Can Be Photochemically Machined

METALS
Aluminum
Aluminum, anodized
Brass
Cold rolled steel
Chromium
Copper, oxygen free
Copper, rolled
Copper, electrolytic
Copper, beryllium
Copper (OFHC)
Elinvar Extra
Elgiloy
Gold
Havar
Inconel
Lead
Magnesium
Manganese
Molybdenum
Molybdenum, cold rolled
Molybdenum, arc cast
Monel
Nickel
Nickel silver
Nichrome
Ni Span C
Permanickel
Phospor bronze
Rehnium
Silver
Steels
- Stainless steel
  - 300 series
- PH 15-7 Steel
- PH 17-7 Steel
- Custom 455
- Spring steel

Tungsten
Udimet
Vanadium
Zinc
Zirconium
90-10 Copper nickel

GLASS TO METAL AND CERIUM TO METAL

ASTM F-15 Alloy
- Kovar
- Rodar
- Nicoseal
- Therlo
- Sealmet 29-17

ASTM F-30 Alloy
- Glass Sealing 42
- 142 Alloy
- Glass Sealing 46
- 146 Alloy
- Glass Sealing 49
- 4750
- Glass Sealing 52
- 152 Alloy

ASTM F-31 Alloy
- Glass Sealing 42-6
- Sylvania No. 4 Alloy
- Sealmet No. 4

SOFT MAGNETIC ALLOYS

44-50% Ni Fe Balance
- High Permeability 49
- 4750 Alloy
- Hipernik
- High Permeability 45

High Permeability Alloys
- Hymu 80
- 4-79 Permalloy
- Hipernom
- Mumetal
- Hymu 800
- Supermalloy
- 5-79 Permalloy

ELECTRICAL SILICON IRONS

Orthosil

CONTROLLED EXPANSION ALLOYS

Invar 36

OTHERS
Plastics
Polyesters
Polymides
Epoxy resins
Glass
Ceramics

SOURCE Photo Chemical Machining Institute, Evanston, IL

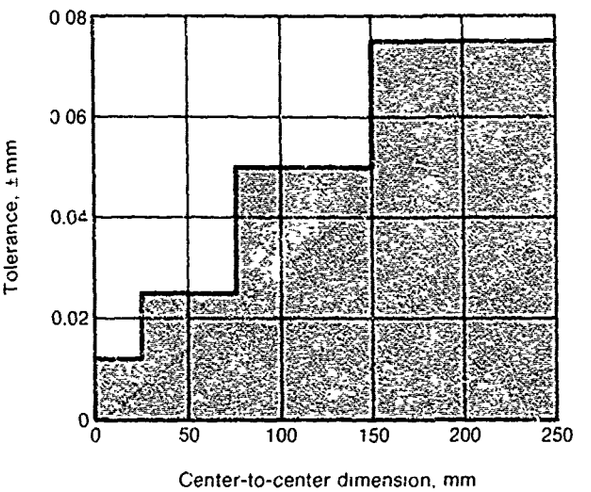


Figure 13.3-3 Practical tolerances on center-to-center dimensions using photochemical milling. (W T Harris, *Chemical milling*, Oxford Clarendon Press, 1976, p. 191)

Surface Technology

Similar to that for CHM.

Equipment and Tooling

Batch and automatic equipment are available for both dip and spray etching of strips up to 2-feet [0.6 ml wide. Some installations include an electrical assist to the light, low-concentration chemicals in order to obtain a straighter cut. Direct-current power, with low current density, is required. Photoreducing and photoreproducing equipment are readily available and can be integrated into continuous blanking lines.

Machining Characteristics

Safety considerations in handling the corrosive chemicals and fumes are similar to those for CHM.

The etch factor for photochemical machining and the circuit board industry, figure 13.3-2, has been defined as the inverse of the ratio used in the chemical machining industry. The tool designer must exercise care to be sure which is applicable in his case.

SELECTED DATA

TABLE 13.3–2 Standard PCM Tolerances for Common Materials

WORKPIECE MATERIAL	TOLERANCE, inch					
	Workpiece Thickness, inch					
	0.001	0.002	0.005	0.010	0.015	0.020
Copper, copper alloys and glass sealing alloys (Nicoseal*)	±0.0002	±0.0005	±0.001	±0.0015	±0.0025	±0.0035
Nickel-silver	±0 0005	±0.001	±0 001	±0.0015	±0.0025	±0 0035
Magnetic Ni-Fe alloys (HyMu 80*)	±0.0005	±0.001	±0.001	±0.0015	±0.0025	±0 0035
Steel	±0.0005	±0.001	±0.0015	±0 0015	—	—
Nickel and stainless steel	±0.0005	±0.001	±0.0015	±0.002	±0 003	—
Aluminum and magnesium	±0.001	±0 0015	±0.0025	—	—	—
Plastics (Mylar†, Kapton†)	±0.001	±0.0015	±0.0025	±0.005	—	—
Molybdenum, titanium and exotics	±0.0005	±0 001	±0.002	—	—	—

WORKPIECE MATERIAL	TOLERANCE, mm					
	Workpiece Thickness, mm					
	0.025	0.050	0.13	0.25	0.38	0.50
Copper, copper alloys and glass sealing alloys (Nicoseal*)	±0.005	±0.013	±0.025	±0.038	±0.063	±0.089
Nickel-silver	±0.013	±0.025	±0.025	±0.038	±0.063	±0.089
Magnetic Ni-Fe alloys (HyMu 80*)	±0.013	±0.025	±0.025	±0.038	±0.063	±0.089
Steel	±0.013	±0.025	±0.038	±0.038	—	—
Nickel and stainless steel	±0.013	±0.025	±0.038	±0.050	±0.076	—
Aluminum and magnesium	±0.025	±0.038	±0.063	—	—	—
Plastics (Mylar†, Kapton†)	±0.025	±0.038	±0.063	±0.13	—	—
Molybdenum, titanium and exotics	±0.013	±0.025	±0.050	—	—	—

SOURCE: ChemPar Corporation, Montgomeryville, PA.

*Registered Trademark—Carpenter Technology Corporation.

† Registered Trademark—E. I duPont deNemours and Co. Inc

13.3 Photochemical Machining—PCM

TABLE 13.3–3 Practical Tolerances Attainable for Prototype and Short PCM Runs

APPROXIMATE FLAT SIZE	TOLERANCE, inch						
	Thickness, inch						
in	0.001	0.002	0.005	0.010	0.015	0.020	0.040
2 x 2	Empirical	±0.0005	±0.0007	±0.0010	±0.0015	±0.0020	±0 0040
8 x 10	Empirical	±0.0007	±0.0010	±0.0015	±0.0020	±0 0030	±0.0050
12 x 18	Empirical	±0.0010	±0.0015	±0.0020	±0.0030	±0 0040	±0.0060
	TOLERANCE, mm						
	Thickness, mm						
mm	0.025	0.050	0.13	0.25	0.38	0.50	1.0
50 x 50	Empirical	±0.013	±0.018	±0.025	±0.036	±0.051	±0.10
200 x 250	Empirical	±0.018	±0.025	±0.038	±0.050	±0.076	±0.13
300 x 450	Empirical	±0.025	±0.038	±0.050	±0.076	±0.10	±0.15

SOURCE: Data courtesy of Photo Chemical Machining Institute.

TABLE 13.3–4 Practical Tolerances Attainable for PCM Production Runs

APPROXIMATE FLAT SIZE	TOLERANCE, inch						
	Thickness, inch						
in	0.001	0.002	0.005	0.010	0.015	0.020	0.040
2 x 2	Empirical	±0.0010	±0.0010	±0.0015	±0.0020	±0.0030	±0.0050
8 x 10	Empirical	±0.0010	±0.0015	±0.0020	±0.0025	±0.0040	±0.0060
12 x 18	Empirical	±0.0015	±0.0020	±0.0025	±0.0035	±0.0045	±0.0070
	TOLERANCE, mm						
	Thickness, mm						
mm	0.025	0.050	0.13	0.25	0.38	0.50	1.0
50 x 50	Empirical	±0.025	±0.025	±0.038	±0.050	±0.076	±0.13
200 x 250	Empirical	±0.025	±0.038	±0.050	±0.063	±0.10	±0.15
300 x 450	Empirical	±0.038	±0.050	±0.063	±0.089	±0.11	±0.18

SOURCE Data courtesy of Photo Chemical Machining Institute.

TABLE 13.3–5 Practical Tolerances for Center-to-Center Dimensions in PCM

CENTER-TO-CENTER DIMENSIONS		TOLERANCES	
in	mm	in	mm
1 0 or less	25 or less	±0.0005	±0.013
1.0 to 3.0	25 to 75	±0.0010	±0.025
3 0 to 6.0	75 to 150	±0.0020	±0.050
6 0 to 10 0	150 to 250	±0.0030	±0.076

SOURCE Data courtesy of Photo Chemical Machining Institute

TABLE 13.3–6 Practical Tolerances for Holes Made by PCM

MATERIAL THICKNESS		PRACTICAL HOLE DIAMETER		TOLERANCES ATTAINABLE	
in	mm	in	mm	in	mm
0.0005	0.013	Empirical	Empirical	Empirical	Empirical
0.0010	0.025	Empirical	Empirical	Empirical	Empirical
0.0020	0.050	0.0030	0.076	±0.001	±0.025
0.0050	0.13	0.0060	0.15	±0.0015	±0.038
0.0070	0.18	0.0080	0.20	±0.0015	±0.038
0 0100	0.25	0.0120	0.30	±0.002	±0.051
0.0200	0.50	0.0260	0.66	±0.003	±0.076

SOURCE Data courtesy of Photo Chemical Machining Institute.

TABLE 13.3–7 Guidelines for Smallest Hole Sizes by PCM

METAL THICKNESS		SMALLEST HOLE DIAMETER
in	mm	
less than 0.001	less than 0.025	Must be determined by test run
0.001 to 0.005	0.025 to 0.13	At least metal thickness
0.005 or over	0.13 or over	At least 110% metal thickness

SOURCE: Data courtesy of Photo Chemical Machining Institute.

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Thermochemical Machining—TCM 13.4
or Thermal Energy Method—TEM

PROCESS SUMMARY

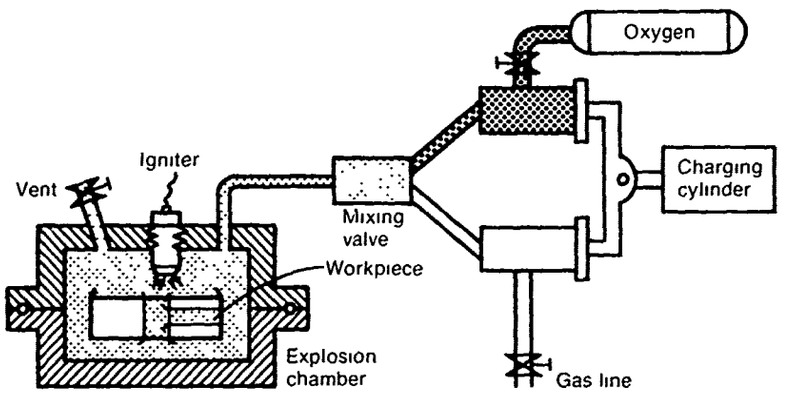


Figure 13.4–1 TCM schematic.

Principles

Thermochemical machining (TCM) removes workpiece material—usually only burrs and fins—by exposure of the workpiece to hot, corrosive gases (see figure 13.4-1). The process is sometimes called combustion machining, thermal deburring, or thermal energy method (TEM). The workpiece is exposed for a very short time to extremely hot gases, which are formed by detonating an explosive mixture. The ignition of the explosive—usually hydrogen or natural gas and oxygen—creates a transient thermal wave that vaporizes the burrs and fins. The main body of the workpiece remains unaffected and relatively cool because of its low surface-to-mass ratio and the brevity of the exposure to high temperatures.

Practical Applications

TCM will remove burrs or fins from a wide range of materials, but it is particularly effective with materials of low thermal conductivity. It will deburr thermosetting plastics—but not thermoplastic materials. Any modest size workpiece requiring manual deburring or flash removal should be considered a candidate for thermal deburring. Die castings, gears, valves, rifle bolts and similar small parts are deburred readily, including blind, internal and intersecting holes in inaccessible locations. Carburetor parts are processed in automated equipment. Thin sections of fragile parts or those made from highly oxidation-resistant materials may be difficult for TCM. As a rule of thumb, the maximum burr thickness should be less than one-fifteenth of the thinnest feature on the workpiece. Uniformity of results and greater quality assurance over hand deburring is a special advantage of TCM.

Operating Parameters

TABLE 13.4–1 Typical Values for TCM Operating Parameters

Gas	
type:	Natural gas and oxygen or hydrogen and oxygen
mixture:	4:1 to 9:1 (oxygen:gas)
pressure (initial):	10 to 370 psi [69 to 255 kPa] (see table 13.4–2)
Thermal wave	
temperature:	Estimated 6,000°F [3,315°C]
time:	1 to 2 microseconds: Mach 8

Material Removal Rates and Tolerances

Burrs are removed in a few milliseconds and the total cycle time is typically 15 to 50 seconds. Handling time is the principal manufacturing rate determinant. Rifle bolts that formerly took 5 minutes each to deburr by hand are being processed with more consistent results at the rate of 2 pieces in 8 seconds in a batch processing setup. The bulk of the workpiece is generally not affected in TCM. With the application of extra energy, radii can be formed. Radiusing is limited by the conductivity of the workpiece material, for example:

radii in steel	0.002 to 0.030 inch [0.05 to 0.76 mm]
radii in aluminum and brass	0.001 to 0.005 inch [0.025 to 0.13 mm]

13.4 Thermochemical Machining—TCM
or Thermal Energy Method—TEM

Surface Technology

Other than the deburring or radiusing action, there is little effect of TCM on the surface of the workpiece. Thermal distortion is not a problem unless extremely close tolerances are involved. There can be a thin recast layer below thick burrs or fins. A thin oxide film is deposited on most parts. These films are easily removed with commercial solvents or washes.

Equipment and Tools

Automatic equipment is commercially available with chambers up to 11 inches [280 mm] diameter and 9 inches [229 mm] high. A cycle time of 15 seconds is possible with this equiment. Fixturing is primarily oriented toward simplifying the movement of workpieces into and out of the processing chamber. Delicate parts may require holding fixtures to withstand buffeting during the thermal shock wave. Bulk loading baskets are used for handling small parts in lots up to hundreds per load.

Machining Characteristics

Surface stains may result if the workpiece is not clean, dry and free of oil before TCM. The equipment has a stout chamber to contain the detonation. Preplanned handling of the pressurized gases is needed. Noise can range from a gentle "ping" to the sharp report like a 22-caliber rifle when the higher pressure settings are used. Even at full load, the average sound emission level generally remains below 85 decibels. Cleaning of the operating chamber is required at regular intervals.

SELECTED DATA

TABLE 13.4–2 Thermal Energy Deburring Parameters

MATERIAL	MIXTURE O_2 TO NATURAL GAS	INITIAL PRESSURE	
		psi	kPa
Thermplastic	9 to 1	10 to 25	69 to 172
Zinc	4.5 to 1	30 to 70	207 to 483
Cast iron	4.5 to 1	50 to 175	345 to 1,206
Aluminum	4.5 to 1	50 to 125	345 to 862
Brass	4.5 to 1	200 to 240	1,378 to 1,655
Steel	4.5 to 1	100 to 220	689 to 1,516
Stainless steel	4.5 to 1	175 to 370	1,206 to 2,551

SOURCE: SURF/TRAN Company, Madison Heights, MI.

NOTE: The pressure or amount of energy required for deburring increases with the heat conductivity of the material to be deburred.

SECTION 14

TOOL MATERIALS

14.1 General Guidelines for Selection of Tool Materials 14–3
14.2 High Speed Steels 14–4
14.3 Cast Alloys 14–6
14.4 Carbides 14–7
14.5 Micrograin Carbides 14–15
14.6 Coated Carbides 14–16
14.7 Ceramic Tool Materials 14–17
14.8 Diamond Tools 14–18

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14.1 General Guidelines for Selection of Tool Materials

Selecting the optimum tool material is a major factor in realizing the full potential of a particular machine tool. While only one type of tool material is specified for some materials and operations in sections 1 through 7, there are a number of cases for which two or three material types are recommended. The following supplemental guidelines are offered as an approach for the logical selection of the best tool materials for machining a specific work material.

1. High speed steel tools are generally used for the following:

   - High volume, low cutting speed operations (for example, in screw machines)
   - Complex tool forms such as form tools, drills, cutoff tools, etc.
   - All sizes of end mills, drills, reamers, taps and gear cutters
   - Certain machining operations on problem materials, such as nickel base high temperature alloys
   - High positive rake requirements

2. Cast alloy cutting tool materials are selected as an intermediate between high speed steel and carbide tool materials. The high cobalt high speed steels also serve as intermediates, and there appears to be a trend for them to supersede the cast alloy tools.

3. Carbide tools are generally applicable when one or more of the following conditions exist:

   - Rigidity of the machine tool, tooling, and workpiece is acceptable.
   - Machine tool power is adequate for higher metal removal rates.
   - Workpiece configuration and machining operation permit higher cutting speeds.
   - High production rates are required.

4. Ceramic tools, high strength carbides, diamond tools, and the cast alloy tools referred to previously have rather specific application in contrast with the wide usage of high speed steel and carbide tools.

14 TOOL MATERIALS

14.2 High Speed Steels

The high speed steels can be classified into three general types as follows:

1. Tungsten high speed steels
2. Molybdenum high speed steels
3. High speed steels containing cobalt

The chemical compositions of the AISI and the ISO high speed steels are listed in tables 14-1 and 14-2, respectively. Note that the type numbers and designations listed in table 14-2 are tentative, having been taken from the proposed draft international standard ISO/DIS 4957.

As a general rule, the tungsten grades such as T1, T2, etc., are not quite as tough as the molybdenum grades but are much simpler to heat treat. The molybdenum high speed steels such as M1, M2, M3, M7 and M10 are much more widely used than the tungsten grades. Both the tungsten and the molybdenum high speed steels can be hardened to 64 to 66 R_c and are recommended for the machining of easy-to-machine materials. These include steels having a hardness up to 350 Bhn. While high speed steel types 1 and 2 can be used in machining steels having a higher hardness, the type 3 high speed steels containing cobalt are recommended. It should be noted that several of the high speed steels such as M3 and M4 contain more vanadium, thus providing increased wear resistance, but at the same time making the grinding of the tools more difficult.

TABLE 14-1 Compositions and Applications of AISI-Type High Speed Tool Steels

TYPE	NOMINAL COMPOSITION, percentage						APPLICATION
	C	W	Mo	Cr	V	Co	
1. Tungsten High Speed Steels							
T1	0.75	18.00	—	4.00	1.00	—	General purpose
T2	0.80	18.00	—	4.00	2.00	—	General purpose—Higher strength
2. Molybdenum High Speed Steels							
M1	0.80	1.50	8.00	4.00	1.00	—	General purpose
M2	0.85	6.00	5.00	4.00	2.00	—	General purpose
M3 Class 1	1.05	6.00	5.00	4.00	2.40	—	Fine edge tools
M3 Class 2	1.20	6.00	5.00	4.00	3.00	—	Fine edge tools
M4	1.30	5.50	4.50	4.00	4.00	—	Abrasion resistant
M7	1.00	1.75	8.75	4.00	2.00	—	Fine edge tools—Abrasion resistant
M10	0.85	—	8.00	4.00	2.00	—	General purpose—High strength
3. High Speed Steels Containing Cobalt							
M6	0.80	4.00	5.00	4.00	1.50	12.00	Heavy cuts—Abrasion resistant
M30	0.80	2.00	8.00	4.00	1.25	5.00	Heavy cuts—Abrasion resistant
M33	0.90	1.50	9.50	4.00	1.15	8.00	Heavy cuts—Abrasion resistant
M34	0.90	2.00	8.00	4.00	2.00	8.00	Heavy cuts—Abrasion resistant
M36	0.80	6.00	5.00	4.00	2.00	8.00	Heavy cuts—Abrasion resistant
M41	1.10	6.75	3.75	4.25	2.00	5.00	Heavy cuts—Abrasion resistant
M42	1.10	1.50	9.50	3.75	1.15	8.00	Heavy cuts—Abrasion resistant
M43	1.20	2.75	8.00	3.75	1.60	8.25	Heavy cuts—Abrasion resistant
M44	1.15	5.25	5.25	4.25	2.25	12.00	Heavy cuts—Abrasion resistant
M46	1.25	2.00	8.25	4.00	3.20	8.25	Heavy cuts—Abrasion resistant
M47	1.10	1.50	9.50	3.75	1.25	5.00	Heavy cuts—Abrasion resistant
T4	0.75	18.00	—	4.00	1.00	5.00	Heavy cuts
T5	0.80	18.00	—	4.00	2.00	8.00	Heavy cuts—Abrasion resistant
T6	0.80	20.00	—	4.50	1.50	12.00	Heavy cuts—Hard material
T8	0.75	14.00	—	4.00	2.00	5.00	General purpose—Hard material
T15	1.50	12.00	-	4.00	5.00	5.00	Extreme abrasion resistant

The high speed steels with cobalt, type 3, contain 5 to 12 percent cobalt. The addition of cobalt provides greater hot hardness and wear resistance but results in a somewhat lower toughness. In general, it has been found that these grades are not particularly advantageous in the machining of the readily machinable materials. They are, however, most beneficial for machining steels having a hardness level above 350 Bhn and for the more difficult-to-machine metals, such as titanium and nickel base high temperature alloys. The T15 grade also has a higher percentage of vanadium; consequently, it is more difficult and more costly to grind than the other high speed steels containing cobalt.

In general, the high speed steels containing cobalt can be heat treated to a hardness level of 65 to 67 R_C. While the M40 series can be hardened to a level of 70 R_C, the hardness range usually recommended is 66 to 68 R_C. Above 68 R_C, high speed steel tools tend to be too brittle for most applications.

High speed steel cutters are widely used for the following machining operations:

Operations using form tools
Screw machine operations
End milling
Drilling
Reaming (carbide-tipped reamers are also widely used)
Tapping (nitrided taps are often used for difficult-to-machine alloys)
Broaching
Gear cutting

A recent development in high speed steels is the availability of indexable inserts made by the powder metal process. The sizes and shapes of the inserts correspond to those of some of the more popular carbide inserts. The current grade selection is limited, but in the future, selection is likely to expand.

TABLE 14–2 Identification and Type Classification of High Speed Tool Steels
(Per ISO/DIS 4957)

TYPE OF STEEL				CHEMICAL COMPOSITION, percentage[4]					
Group	ISO No.[a]	AISI No.[b]	Designation[a,c]	C	Co[d]	Cr	Mo[d]	V	W
Basic types	S1	T1	HS 18-0-1	0.73 to 0.83	—	3.50 to 4.50	—	0.90 to 1.20	17.2 to 18.7
	S2	M7	HS 2-9-2	0.95 to 1.05	—	3.50 to 4.50	8.20 to 9.20	1.70 to 2.20	1.50 to 2.10
	S3	M1	HS 1-8-1	0.77 to 0.87	—	3.50 to 4.50	8.00 to 9.00	0.90 to 1.40	1.40 to 2.00
	S4	M2	HS 6-5-2	0.82 to 0.92	—	3.50 to 4.50	4.60 to 5.30	1.70 to 2.20	5.70 to 6.70
Increased C + V-content	S5	M3	HS 6-5-3	1.15 to 1.30	—	3.50 to 4.50	4.60 to 5.30	2.70 to 3.20	5.70 to 6.70
With Co-content	S6	use T5	HS 18-0-1-10	0.75 to 0.85	9.50 to 10.5	3.50 to 4.50	—	1.30 to 1.80	17.2 to 18.7
	S7	use T4	HS 18-1-1-5	0.75 to 0.85	4.70 to 5.20	3.50 to 4.50	0.70 to 1.00	1.10 to 1.60	17.2 to 18.7
	S8	M35	HS 6-5-2-5	0.85 to 0.95	4.70 to 5.20	3.50 to 4.50	4.60 to 5.30	1.70 to 2.20	5.70 to 6.70
Increased C + V content + Co	S9	T15	HS 12-1-5-5	1.45 to 1.60	4.70 to 5.20	3.50 to 4.50	0.70 to 1.00	4.75 to 5.55	11.5 to 13.0
	S10	—	HS 10-4-3-10	1.20 to 1.35	9.50 to 10.5	3.50 to 4.50	3.20 to 3.90	3.00 to 3.50	9.00 to 10.0
Increased C-content + Co	S11	M42	HS 2-9-1-8	1.05 to 1.20	7.50 to 8.50	3.50 to 4.50	9.00 to 10.0	0.90 to 1.40	1.30 to 1.90
	S12	M41	HS 7-4-2-5	1.05 to 1.20	4.70 to 5.20	3.50 to 4.50	3.50 to 4.20	1.70 to 2.20	6.40 to 7.40

[a] The type numbers and designations are tentative and will be subject to alteration when the relevant International Standards have been established.

[b] Approximate AISI equivalent—See table 14–1.

[c] Successively W-Mo-V-Co.

[d] For all steels: Silicon < 0.50%, Manganese < 0.40%, Phosphorus < 0.030%, and Sulphur < 0.030%.

[e] A dash in these columns indicates that these alloying elements should not be intentionally added to the heat and, that in the case of cobalt, the content of the cast should not exceed 1.00% and, in the case of molybdenum, it should not exceed 0.70%.

14 TOOL MATERIALS

14.3 Cast Alloys

Cast alloys have been available for many years. These materials are generally cobalt-chrome-tungsten alloys with carbon and other alloy additions. They are not heat treatable, and the maximum hardness (55 to 65 R_c) occurs near the cast surface. As a result, cast alloy tools must be used as-cast with as little grinding as possible.

Cast alloy materials are not widely used. However, they find limited use as a compromise since they perform well at higher surface speeds than conventional high speed steels and are more resistant to chipping than standard carbide grades. A number of cast alloy tool materials and their compositions are shown in table 14-3.

TABLE 14-3 Cast Alloy Tool Materials

TRADE NAME	NOMINAL COMPOSITION percentage					HARDNESS, R_c	MANUFACTURER
	Co	Cr	W	C	OTHERS		
Blackalloy 525	44 0	24.0	20.0	2.0		61 to 63	Blackalloy Company of America, Inc. Paterson, NJ
Blackalloy T.X. 90	42.0	24.0	22.0	2.0		63 to 65	
Haynes Stellite R 98M2 alloy	38.0	30.0	18 5	2.0	1 2% boron, 4%V, 4% nickel	63	Co-Bo Cast Tool Co. Inc. Kokomo, IN
Haynes Stellite R Star J metal	43.0	32.5	17.5	2.5		61	
Haynes Stellite R alloy No. 3	50.0	31.0	12.5	2.4		59	
Haynes Stellite R alloy No. 19	53.0	31.0	10.5	1.8		55	
Tantung G	47.0	30.0	15.0	3.0	5% Ta or Cb	60 to 63	Fansteel, VR/Wesson Division Waukegan, IL
Tantung 144	45.0	28.0	19.0	3.0	6% Ta or Cb	62 to 64.5	

NOTES: The procedure used for making cast alloy tools is to melt the particular analysis in an electric furnace and then cast the tools to shape with small stock allowance for finish grinding. The tools are at maximum hardness when removed from the molds and cannot be hot or cold worked and do not respond to heat treatment

"Haynes Stellite" is a registered trademark of Cabot Corporation.

This chart is not to be considered an endorsement of any manufacturer's product or an approved list of any manufacturer's products.

14.4 Carbides

Each tool manufacturer listed in table 14-4 has a wide variety of carbide grades so that a specific grade can be selected for a given material and operation. Although most of the carbide grades are listed under the industry code (C-1, C-2, etc.) in table 14-5, this does not necessarily imply that the various manufacturers' grades under a specific code are equivalent.

The C-1 through C-4 grades are straight tungsten carbide bonded with cobalt and vary chiefly in cobalt content and grain size. They are widely used for machining cast irons, high temperature alloys, work hardening stainless steels, abrasive nonmetallic materials and nonferrous metals including titanium. Toughness decreases and hardness increases proceeding from C-1 to C-4. The C-2 grades provide a good compromise in properties and may be categorized as "general purpose" for the aforementioned materials.

The C-5 through C-8 grades include those which contain various combinations of tungsten carbide, tantalum carbide and titanium carbide bonded with cobalt. The C-8 category now also includes tools of straight titanium carbide bonded with molybdenum (or molybdenum carbide) and nickel. Other straight titanium carbide grades with properties in the C-5 through C-7 range are also available. Grades C-5 through C-8 are generally recommended for machining steels because they provide better crater resistance than the C-1 to C-4 grades. Toughness decreases and the hardness increases in going from C-5 to C-8. The C-6 grades are for general-purpose use.

For work materials such as highly alloyed cast irons, alloy steels over 50 R_c, ferritic or martensitic stainless steels and some high temperature alloys, the preferred carbide grades may come from either the C-1 to C-4 or the C-5 to C-8 group.

Table 14-6 has been used in classifying carbides according to use as specified by the International Organization for Standardization (ISO). Recommended grades produced by various manufacturers are listed according to ISO classifications in table 14-7.

TABLE 14-4 Carbide Manufacturers (Carbide Grade Chart)

CARBIDE	MANUFACTURER
Adamas	ADAMAS CARBIDE CORPORATION, Kenilworth, NJ
Atrax	ATRAX RESEARCH & DEVELOPMENT CENTER, Wallace-Murray Corporation, Tuscaloosa, AL
Carboloy	CARBOLOY SYSTEMS DEPARTMENT, General Electric Company, Detroit, MI
Carmet	CARMET COMPANY, A Member Company of Allegheny Ludlum Industries, Madison Heights, MI
DoAll	DOALL COMPANY, Des Plaines, IL
Duramet	DURAMET CORPORATION, Warren, MI
Ex-Cell-O	EX-CELL-O CORPORATION, Detroit, MI
Greenleaf	GREENLEAF CORPORATION, Saegertown, PA
GTE (Walmet)	GTE SYLVANIA INCORPORATED, Walmet Division, Royal Oak, PA
Iscar	ISCAR METALS, INC., Edison, NJ
Kennametal	KENNAMETAL INC., Latrobe, PA
Newbide	NEWCOMER PRODUCTS, INC., Latrobe, PA
Sandvik (Coromant)	SANDVIK, INC., Fair Lawn, NJ
Seco	SECO TOOLS INC., Northbrook, IL
Talide	METAL CARBIDES CORPORATION, Youngstown, OH
Teledyne (Firthite)	TELEDYNE FIRTH STERLING, Pittsburgh, PA
TRW Wendt-Sonis	WENDT-SONIS DIVISION, TRW Inc., Rogers, AR
Tungsten Alloy	TUNGSTEN ALLOY MANUFACTURING CO., INC., Harrison, NJ
Ultra-Met	ULTRA-MET MANUFACTURING COMPANY, Farmington, MI
Valenite	THE VALERON CORPORATION, Oak Park, MI
VR/Wesson	FANSTEEL, VR/Wesson Division, Waukegan, IL

TABLE 14–3 Carbide Grade Chart, C Grade

TRADE NAME	INDUSTRY CODE							
	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8
Adamas	B	A AM ACT-2†	PWX ACT-2†	GU-2	499 434 ACT-5† AG-5‡ 474 Titan 50*	ACT-5† AG-5† 495 Titan 60*	548 ACT-7† Titan 80*	490 ACT-7† Titan 80* Titan 100*
Atrax	M-22	A6	A7	A7	T3 T50 T56 T50C	T50 T64 T65	T63 T76 T78 T76C	T8
Carboloy	518† 44A 320	570§ 515† 523† 883	545§ 570§ 515† 523† 895	210 545§ 999 570§	518† 370 375 390	570§ 515† 516† 350 518† 370	545§ 570§ 515† 516† 350	210* 320
Carmet	CA-12 CA-3	CA-310 CA-4 CA-443 CA-8443† CA-9443#	CA-7 CA-8443† CA-9443# R-03*	CA-8 R-03*	CA-610 CA-740 CA-721 CA-9740# CA-9721#	CA-606 CA-720 CA-9720#	CA-711 CA-9711#	CA-704 R-03*
DoAll	DO-1 DO-30	DO-2 DO-20 DO-46†	DO-3	DO-4 DO-80	DO-15 DO-35 DO-44†	DO-16 DO-36 DO-40†	DO-17 DO-34 DO-42†	DO-18 DO-80
Duramet	DU1	DU2 DU22	DU3	DU4	DU5 DU55	DU6	DU7 DU78	DU8
Ex-Cell-o	E-8	E-6 XLO-28 XLO-620 XL-202††	E-5 XL-202††	E-3	10A 8A XL-602††	8A 606 6A XL-85* XL-602††	6AX XLO-61 XL-86*	509 XL-88*
Greenleaf	G-01 G-10	G-02 G-20/G-30 G-1 Ti-2	G-30 G-1 Ti-2	G-1 G-40	G-50 G-53 G-52 GA-5 Ti-5	Ti-6/GA-6 G-60 G-54	GA-6/G-1/ Ti-6 G-70/G-25	Ti-6 GA-6/G-1 G-80/G-88
G.T.E. (Walmet)	WA-110 WA-1 WA-59	WA-2 P-2# WA-35 WA-69 WA-63	WA-3 P-3#	WA-4 P-4#	WA-54 P-54# WA-5 P-5# WA-57 P-57#	WA-47 P-47#	WA-7 WA-73 P-47#	WA-8
Iscar	IC 28	IC 2 IC 20 IC 24 IC 424	IC 20 IC 424	IC 4	IC 50 IC 50M IC 54 IC 656 IC 757	IC 50M IC 70 IC 656 IC 757	IC 70 IC 78 IC 60T IC 80T IC 757	IC 80T
Kennametal	K1 KC250††	K6 K68 K8735 KC210†† KC250†† KC910§	K68 KC210†† KC910§	K11 KC910§	K420 KC850††	K420 K21 K2884 KC810†† KC850†† KC910§	K4H K45 KC810†† KC850†† KC910§	K7H K165* KC910§
Newbe[illegible]	N-10	N-22 NT-2 N25 NT25	N-30 NT-2 N20 NT25	N-40 NT25	N-50/N-52 NT-5 N55 NT55	N-60 NT55 NT6	N-70/N-72 NT-6 NT55	N-80 N-93/N-95 NT6
CAST IRON, NONFERROUS AND NONMETALLIC MATERIALS C-1 Roughing C-2 General Purpose C-3 Finishing C-4 Precision Finishing					STEEL AND STEEL ALLOYS C-5 Roughing C-6 General Purpose C-7 Finishing C-8 Precision Finishing			

NOTE: Listings do not necessarily imply equivalency of various manufacturers' grades. This chart is not to be considered an endorsement of or an approved list of any manufacturer's products.

*Contains more than 50% titanium carbide.

†TiC coated.

‡TiN over TiC coated.

§Al_2O_3 coated.

#Tri-Phase titanium nitride coated.

**Al_2O_3 and TiC coated.

††Coated.

‡‡Triple-coated, Ti-C + Ti(C, N) + Al_2O_3.

Table 14–5—Continued

TRADE NAME	INDUSTRY CODE							
	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8
Sandvik (Coromant)	H20 HML	GC015** GC315† GC1025† H1P H20 HM HML GC310** GC320** GC135† IRB	GC015** GC315† GC1025† H1P H10 HM GC310** GC320** GC135† IRB	GC015** H05 H1P H10 GC310**	S6 SM30 GC135† S6/S4 GC1025† S35	GC1025† GC015** GC135† S4 SM SM30 S35 GC120#	GC1025† GC015** SIP S2 SM SM30 GC135† GC120#	GC015** SIP F02# GC1025† GC120#
Seco	HX	SU41 HX TP15‡‡ T15M‡‡	H13 TX10‡‡ SU41 HX TP15‡‡ T15M‡‡	TX10‡‡ TP15‡‡ T15M‡‡	G27 S4 S6 S60M TP35† S25M	S2 SU41 S25M S10M TP25† TP35† TP15‡‡	S25M S10M S1F TP15‡‡ TP25†	S1G TP15‡‡
Talide	C-89	C-91	C-93 C-936	C-95	S-880	S-901	S 92	S-94
Teledyne (Firthite)	H-91 H-17 H-6	H-21 HTA HA HN + †† TC + ††	HA HTA HN + †† TC + †† HF SD-3#	HN + †† TC + †† HF SD-3#	T-04 T-14 HN + 4†† TC + 4†† NTA HN + †† TC + ††	HN + †† TC + †† TXH T-22 T-24	HN + †† T-25 TC + 1†† SD-3#	HN + †† TC + 1†† SD-3#
TRW Wendt-Sonis	TRW-167‡ CQ-22T† CQ-22 CQ-12	TRW-027‡ U222† CQ-2 CQ-23	TRW-237‡ CQ-23T† CQ-23 CQ-3	TRW-237‡ CQ-23T† CQ-4 CQ-23	CY-12‡ CY-16‡ CY-17‡ U225† TRW-715† TRW-716† CY-17 CY-12	TRW-716‡ U225† CY-16	TRW-714‡ U227† CY-14 Ti8#	TRW-731‡ CY-31T† CY-31 Ti8#
Tungsten Alloy	A6	6B 6BH 10F	4B	3B	11T 10T 9S	10T 9S	8T	5S
Ultra-Met	Z-1 Z-10 Z-25 Z-9	Z-2 Z-20	Z-20 Z-3	Z-4	Z-5 Z-52 Z-517 Z-50	Z-50 Z-6 Z-60	Z-7 Z-70 Z-71 Z-8	Z-8 Z-80#
Valenite	V-1N†† VC-1 VC-111 VC-101	V-01** V-91† V-88† VN-8‡ VN-2†† V-1N†† VC-2 VC-24 VC-27 VC-28 VC-29	V-01** V-91† V-88† VN-8‡ VN-2†† VC-3 VC-29	V-01** VC-3 VC-23	V-88† VN-8‡ V-99† VN-5†† V-1N†† VC-5 VC-55 VC-56 VC-125	V-01** V-99† V-90† V-88† VN-8‡ VN-5†† VC-6	V-01** V-90† V-88† VN-8‡ VN-5†† VC-7 VC-76	V-01** VC-83# VC-8
VR/Wesson	2A3 2A68 VR-54 Ramet-1	2A5 VR-82 630† Ramet-1	VR-82 630† 2A7	2A7 630† VR-65#	650† 660† VR-77	650† 660† VR-75 VR-77	660† 670† VR-73	VR-65# VR-71 670†
	CAST IRON, NONFERROUS AND NONMETALLIC MATERIALS C-1 Roughing C-2 General Purpose C-3 Finishing C-4 Precision Finishing				STEEL AND STEEL ALLOYS C-5 Roughing C-6 General Purpose C-7 Finishing C-8 Precision Finishing			

*Contains more than 50% titanium carbide.
†TiC coated
‡TiN over TiC coated.
§Al_2O_3 coated
#Tri-Phase titanium nitride coated.
**Al_2O_3 and TiC coated
††Coated.
‡‡Triple-coated, Ti-C + Ti(C, N) + Al_2O_3

TABLE 14–6 Classification of Carbides According to Use, per ISO 513-1975(E)

MAIN GROUPS OF CHIP REMOVAL			GROUPS OF APPLICATION			DIRECTION OF INCREASE IN CHARACTERISTIC	
Symbol	Broad Categories of Material To Be Machined	Distinguishing Colors	Designation	Material To Be Machined	Use and Working Conditions	Of Cut	Of Carbide
P	Ferrous metals with long chips	Blue	P 01	Steel, steel castings	Finish turning and boring; high cutting speeds, small chip section, accuracy of dimensions and fine finish, vibration-free operation	Increasing feed	Toughness
			P 10	Steel, steel castings	Turning, copying, threading and milling, high cutting speeds, small or medium chip sections		
			P 20	Steel, steel castings Malleable cast iron with long chips	Turning, copying, milling, medium cutting speeds and chip sections, planing with small chip sections		
			P 30	Steel, steel castings Malleable cast iron with long chips	Turning, milling, planing, medium or low cutting speeds, medium or large chip sections, and machining in unfavorable conditions.*		
			P 40	Steel Steel castings with sand inclusion and cavities	Turning, planing, slotting, low cutting speeds, large chip sections with the possibility of large cutting angles for machining in unfavorable conditions* and work on automatic machines		
			P 50	Steel Steel castings of medium or low tensile strength, with sand inclusion and cavities	For operations demanding very tough carbide. turning, planing, slotting, low cutting speeds, large chip sections, with the possibility of large cutting angles for machining in unfavorable conditions* and work on automatic machines	Increasing speed	Wear resistance
M	Ferrous metals with long or short chips and nonferrous metals	Yellow	M 10	Steel, steel castings, manganese steel Gray cast iron, alloy cast iron	Turning, medium or high cutting speeds Small or medium chip sections	Increasing feed	Toughness
			M 20	Steel, steel castings, austenitic or manganese steel, gray cast iron	Turning, milling. Medium cutting speeds and chip sections.		
			M 30	Steel, steel castings, austenitic steel, gray cast iron, high temperature resistant alloys	Turning, milling, planing. Medium cutting speeds, medium or large chip sections.		
			M 40	Mild free cutting steel, low tensile steel Nonferrous metals and light alloys	Turning, parting off, particularly on automatic machines.	Increasing speed	Wear resistance

*Raw material or components in shapes which are awkward to machine. casting or forging skins, variable hardness, etc , variable depth of cut, interrupted cut, work subject to vibrations.

TABLE 14-6—Continued

MAIN GROUPS OF CHIP REMOVAL			GROUPS OF APPLICATION			DIRECTION OF INCREASE IN CHARACTERISTIC	
Symbol	Broad Categories of Material To Be Machined	Distinguishing Colors	Designation	Material To Be Machined	Use and Working Conditions	Of Cut	Of Carbide
K	Ferrous metals with short chips, nonferrous metals and nonmetallic materials	Red	K 01	Very hard gray cast iron, chilled castings of over 85 Shore, high silicon aluminum alloys, hardened steel, highly abrasive plastics, hard cardboard, ceramics.	Turning, finish turning, boring, milling, scraping.	Increasing feed	Toughness
			K 10	Gray cast iron over 220 Brinell, malleable cast iron with short chips, hardened steel, silicon aluminum alloys, copper alloys, plastics, glass, hard rubber, hard cardboard, porcelain, stone.	Turning, milling, drilling, boring, broaching, scraping.		
			K 20	Gray cast iron up to 220 Brinell, nonferrous metals: copper, brass, aluminum	Turning, milling, planing, boring, broaching, demanding very tough carbide.		
			K 30	Low hardness gray cast iron, low tensile steel, compressed wood	Turning, milling, planing slotting, for machining in unfavorable conditions* and with the possibility of large cutting angles		
			K 40	Soft wood or hard wood Nonferrous metals	Turning, milling, planing, slotting, for machining in unfavorable conditions* and with the possibility of large cutting angles.	Increasing speed	Wear resistance

*Raw material or components in shapes which are awkward to machine· casting or forging skins, variable hardness, etc., variable depth of cut, interrupted cut, work subject to vibrations

TABLE 14–7 Carbide Grade Chart, ISO Grade

TRADE NAME	Group P											Group M						Group K						
	◄ harder ►											◄ harder ►						◄ harder ►						
	◄ tougher ►											◄ tougher ►						◄ tougher ►						
	P01	P05	P10	P15	P20	P25	P30	P35	P40	P45	P50	M05	M10	M15	M20	M30	M40	K01	K05	K10	K15	K20	K30	K40
Adamas	T100	490 ACT7 T80	548 ACT7 T80	495 ACT5 ACT7 T60	495 AG5 ACT5 T60	499 ACT5 T50 AG5	499 ACT5 AG5 T50	ACT5 AG5 499 434	474 ACT5 AG5 434	474	GG		548	548	548	434	474	GU2	GU2	ACT2 PWX	ACT2 PWX	ACT2 AM	B	BB
Atrax	AT8 T76C	T76C AT8	T76 T76C		T50C T65	T50C T56	T50 T50C T56		T3			AT8			T50	T56		A7	A7	A6		M22	M30	M31
Carboloy	210 320	545 329	545 570 515 516 350	570 515 516 350 370	570 515 516 518 370	570 515 516 518 370	570 515 516 518 370	515 516 518 370 390	516 518 370 375 390 395	518 370 375 390 395	370 390	545 570 523	545 570 523 895	570 523 895 883	570 523 883 518 370	523 883 518 370 820	883 44A 820	545 999 570	545 570 523 895	570 523 895 883	570 523 895 883 518	570 523 895 883 518	523 883 518 820	883 44A 820
Carmet	CA 704 R03	CA 711 CA 9711 R03	CA 711 CA 9711	CA 9720 CA 606	CA 606 CA 720 CA 9720	CA 721 CA 9721	CA 721 CA 9721	CA 721 CA 9721	CA 610 CA 740 CA 9740	CA 610 CA 740 CA 9740	CA 610 CA 740	CA 9443 R03	CA 310 CA 711 CA 9443 CA 9721 CA 443	CA 310 CA 711 CA 9443 CA 9721 CA 443	CA 310 CA 721 CA 9721 CA 9740 CA 9443 CA 443	CA 721 CA 740 CA 9740 CA 443	CA 740	CA 8 R03	CA 7 CA 8443 CA 9443	CA 310 CA 8443 CA 9443	CA 310 CA 443 CA 8443 CA 9443	CA 310 CA 4 CA 443	CA 310 CA 3	CA 12
DoAll	D018	D019	D017 D042	D042	D016 D040 D044	D015 D040 D044	D015 D040 D044	D035	D035	D035		D018	D017	D034	D016	D015	D035	D018		D02 D03 D020 D046	D02 D046	D02 D046	D01	D011
Duramet		DU6 DU7	DU6	DU55	DU5 DU55	DU55													DU4	DU3	DU22	DU2 DU22	DU1	
Ex-Cell O	6AX 609 XL88 XL602	6AX XL88 XL602	6AX XL061 XL88 XL602	XL061 XL602	6A 606 XL061 XL86 XL602	XL602	8A XL85 XL602	8A	8A		10A XL502	EA	EA	EA	EA	EA	EA	E3		E5 XL028 XL202	XL202	E6 XL202 XL620	E6 E8	E9
GTE (Walmet)	WA8	WA73	WA7 P-47	WA7 P-47 P-5	WA47 P-47 P-5	WA5 WA47 P-47 WA57 P-5	WA5 P-5 WA57 P-47	WA5 P-5 P-54	WA54 P-54 P-5	WA54 P-54	WA54		WA69		WA63			WA4	WA3	P-2 WA3 WA2 WA35	WA35 WA2 P-2	WA2 P-2	WA1 WA59 WA10	

NOTE: Listings do not necessarily imply equivalency of various manufacturers' grades. This chart is not to be considered an endorsement of or an approved list of any manufacturers' products.

TABLE 14-7—Continued

TRADE NAME	Group P											Group M						Group K						
	◀ harder tougher ▶											◀ harder tougher ▶						◀ harder tougher ▶						
	P01	P05	P10	P15	P20	P25	P30	P35	P40	P45	P50	M05	M10	M15	M20	M30	M40	K01	K05	K10	K15	K20	K30	K40
Greenleaf	G80	G1 G70 G80	G1 G70 G74 GA6 Ti6	G1 G70 G74 GA6 Ti6	G1 G52 G53 G54 G74 GA5 GA6 Ti5 Ti6	G1 G52 G53 G54 G74 GA5 GA6 Ti5 Ti6	G1 G52 G54 GA5 GA6 Ti5 Ti6	G1 G50 GA5 G53 G54 GA5 GA6 Ti5 Ti6	G50 G52 GA5 Ti5	G01 G50 Ti5	G01	G02	G1 G02 G74 GA6 Ti2 Ti6	G1 G02 G10 G52 G74 GA5 GA6 Ti2 Ti5 Ti6	G1 G10 G52 G74 GA5 GA6 Ti2 Ti5 Ti6	G10 G50 G52 GA5 Ti5	G01 G50	G25 G40	G23 G25 G30 G40 Ti2	G02 G23 G25 G30 GA6 Ti2 Ti6	G1 G02 G10 G23 G25 G30 Ti2	G02 G10 G23 G25 Ti2	G02 G10	
Iscar	IC80T	IC60T IC80T	IC60T IC78 IC757	IC757	IC70 IC656 IC757	IC50M IC656 IC757	IC50 IC50M IC656 IC757	IC54 IC656 IC50M	IC54 IC656 IC50M	IC54	IC54		IC24	IC24	IC24	IC28	IC28	IC4	IC424	IC20 IC424	IC424	IC20 IC20 IC424	IC28	IC12 IC28
Kennametal	K165 KC910	K7H KC910	K7H K45 KC810 KC850 KC910	K45 KC810 KC850 KC910	K4H K2884 KC810 KC850 KC910	K21 K2884 KC810 KC850 KC910	K21 K420 KC810 KC850	K21 K420 KC810 KC850	K420 K21 KC850	K420 KC850	K420	K7H KC910	K45 KC810 KC850 KC910	K4H KC810 KC850 KC910	K4H K2884 KC810 KC850 KC910	K420 K21 KC850	K420 K21	K11 KC910	K11 KC210 KC910	K68 KC210 KC910	K68 KC210 KC910	K6 KC210 KC250 KC910	K1 KC250	K1
Newtide	N93 N95 NT6	N80 NT6	N70 N72 NT6 NT55	N72 NT6 NT55	N60 NT5 NT6 NT55	N50 N55 NT55	N50 N52 N55 NT55	N52	N52	N52	N52	N40 N80 NT2	N20 N60 NT25 NT55	N20 N60 NT25 NT55	N22 N25 N55 NT25 NT55	N22 N25 N55 NT55	N10 N52	N40	N20 NT25	N20 NT25	N20 NT25	N22 NT2 N25 NT25	N10	N10
Sandvik (Coromant)	F02 S1P	GC01 S1P	GC015 GC 1025 S1P GC120	GC015 GC 1025 S1P SM GC120	GC015 GC 1025 S2 SM SM30 GC135 GC120	GC015 GC 135 GC 1025 S4 SM SM30 GC120	GC015 GC 135 GC 1025 S4 SM SM30 S35 GC120	GC135 GC 1025 S4 S6 SM30 S35	GC135 S6 SM30 S35	GC135 R1 S6	R4		R1P GC 015	GC135 GC 315 SH GC015	GC135 GC 315 H20 SH GC015	H20 S6 GC 135	R4 S6	H1P H05	GC015 GC 315 GC 1025 H1P H05 H10 GC310	GC015 GC 315 GC 1025 H1P H10 HM GC310 GC320 IRB GC135	GC015 GC 315 GC 1025 H1P H10 HM GC310 GC320 IRB GC135	GC015 GC 315 GC 1025 H1P H20 HM HML GC310 GC320 IRB GC135	H20 HML	
Seco		S1G TP15	S1G S1F TP15 TP25 S10M	S1G S1F S2 TP15 TP25 TP35 S10M	S1F S2 TP15 TP25 TP35 S10M S25M	S2 S4 TP15 TP25 TP35 S10M S25M	S4 TP15 TP25 TP35 S25M	S4 TP25 TP35 S25M S60M	S6 TP35 S25M S60M	S6 S60M	S6 S60M	TP15 TX10	SU41 TP15 TP25 TX10	SU41 TP15 TP25 TP35 TX10 S10M	SU41 G27 TP15 TP25 TP35 S10M S25M S60M	G27 TP15 TP25 TP35 S10M S25M S60M	S6 G27 TP35 S25M		TP15 TX10 T15M	H13 TP15 TP25 TX10 T15M	H13 HX TP15 TP25 TX10 T15M	H13 HX TP15 TP25	HX TP25	
Talide	S94		S92		S901		S880											C35		C93 C936		C91	C89 C99	

TABLE 14–6—Continued

TRADE NAME	Group P											Group M						Group K						
	harder ◄ ► tougher											harder ◄ ► tougher						harder ◄ ► tougher						
	P01	P05	P10	P15	P20	P25	P30	P35	P40	P45	P50	M05	M10	M15	M20	M30	M40	K01	K05	K10	K15	K20	K30	K40
Teledyne (Firthite)	HN+ SD3 TC+1	HN+ SD3 TC+1	HN+ SD3 T25 TC+1	HN+ T-24	HN+ T-24 T22 TC+ TXH	HN+ NTA TC+	HN+ T-14 TC+	HN+4 TC+4	HN+4 TC+4 T04	HN+4 TC+4	H91 HN+4 TC+4	SD3	HN+ TC+1	HN+ T-24	HN+ TC+ TXH	HN+4 TC+4	H91 HN+4 TC+4	HF HN+ TC+1	HN+ HF SD3 TC+1	HA HTA HN+ TC+1	HN+ HTA TC+1	H21 HN+ TC+1	H17	H91
TRW Wendt Sonis	731 CY31T Ti8 714 U227 CY31	714 U227 Ti8 CY31 731 CY31T	714 U227 715 CY14 716 U225	714 U227 715 CY14 716 U225	714 U227 715 CY14 716 U225 CY16	715 716 U225 CY16 CY17T	715 716 U225 CY16 CY17	715 716 U225 CY16 CY17	716 715 U225 CY16 CY17	717 715 CY17T CY17	CY17 717 CY17T	731 CY31 027 U222 U227 CQ23	714 U227 715 716 U225 U222 CY14 CQ2	U227 715 716 U225 U222 CY14 CQ2	716 U225 715 U227 U222 CY16 CY14 CQ2	716 U225 715 U222 CY16 CY14 CQ2	CY17 717 CQ12 CY16 CQ2	CQ4 CQ23 237 CQ23T	U222 CQ23 027 CQ4	CQ2 CQ23 U222 237 027	U222 CQ2 CQ23 027 237	U222 CQ2 CQ23 027 CQ22	CQ2 CQ12 CQ22 U222 027	CQ22 CQ2 CQ12 CQ13
Tungsten Alloy		5S	8T		9S 10T		11T											3B		4B		6B	A6	A9
Ultra-Met	Z-8 Z-80 ZT-70	Z-8 ZT-70	Z-70 Z-71 ZT-70 ZT-60 Z-7	Z-70 ZT-70 ZT-60 ZT-60 Z-6	Z-60 Z-50 Z-6 ZT-50 ZT-60 ZT-6	ZT-52 ZT-50 Z-50	ZT-50 ZT-52 Z-50 Z-52	ZT-517 ZT-52 Z-52 Z-517 Z-50	Z-517 Z-52 ZT-5 ZT-52	Z-52 ZT-5 ZT-52	Z-5 Z-52	Z-8 ZT-7 ZT-2	Z-71 Z-70 ZT-70 ZT-2 Z-2 Z-20	Z-70 ZT-70 ZT-50 Z-2 Z-20 ZT-2	Z-60 Z-50 ZT-60 ZT-50 Z-2 ZT-2	Z-1 Z-10 Z-25 Z-50 ZT-52 Z-2	Z 1 Z-25 Z-52	Z 4 ZT-3	Z-3 ZT-20 Z-20	Z-20 ZT-2 ZT-20 Z 3	Z-2 Z-20 ZT-2	Z-2 Z-25 ZT-2 ZT-25	Z 25 Z-10 Z 1	Z-1 Z-25 Z-9
Valenite	V-01 VC-83 VC-8	V-01 V-88 VC-8 VC-76	V-01 V-90 V-88 VN-8 VN-5 VC-7 VC-76	V-01 V-90 V-88 VN-8 VN-5 VC-76 VC-6 VC-125	V-01 V-90 V-88 VN-8 VN-5 V-99 VC-6 VC-55 VC-125	V-01 V-90 V-88 VN-8 VN-5 V-99 VC 5 VC-55 VC-125	V-01 V-88 VN-8 V-99 VC-5 VC-55	V-88 VN-8 V 99 V-1N VC-56	V-99 V-1N VC-56	V-1N		V-01	V-01 V-88 VC-23	V-01 V-88 VN-8 VN 5 VC-27 VC-23	V-01 V-88 VN 8 VN-5 VC-5 VC-28 VC-27 VC-24 VC-23	V-01 V-88 VN 8 V-1N VC 5 VC-28 VC-24	V-1N VC 111 VC-101	V 01 VC 3	V-01 V-91 V-88 VC 3	V-01 V-91 V 88 VN-8 VN-2	V-01 V-91 V-88 VN 8 VN 2 VC 2 VC-24 VC-29	V-01 V-91 V 88 VN-8 VN-2 VC 2 VC-29 VC-28 VC-24	VN-8 V-1N VC-2 VC-28 VC-24 VC 1 VC 111 VC 101	V-1N VC-111 VC-101
VR/Wesson	VR65 VR71 670	VR65 670	6/0 VR73 660	670 660	650 660 670 VR7	650 660 VR75 VR77	650 660 VR77	VR77 650	650	650		VR65 630	VR73 660 630	VR75 660 630	VR77 VR75 630 VR82 660	VR77 630 VR82 650			630	2A5 2A7 630 VR82	2A5 630 VR82	2A5 630 VR54	2A68 Ramet 1 VR51	2A3 Ramet 1

14.5 Micrograin Carbides

A relatively new group of high strength carbides intended for machining applications is now available. These tungsten carbide-cobalt base materials are characterized by strength levels previously found only in impact and rock bit grades, coupled with much higher levels of hardness, as shown in figure 14-1. Their properties are achieved by various proprietary processes and depend in part on achieving and maintaining a very fine carbide grain size.

Manufacturers recommend these materials for improving metal removal rates and tool life over those possible with high speed steels for conditions where carbides with normal strength levels would chip or break. The major use of micrograin carbides at present is in cutoff and form tools, replacing high speed steel in low-surface-speed, high-production operations on screw machines and similar equipment. Some application is also being found for micrograin carbide tools in the machining of problem materials such as the high temperature alloys and for making punch and die sets intended for extended use.

The high edge-strength of micrograin carbides allows the use of high speed steel tool geometry and, when necessary, speeds as low as those used with high speed steels. Conversely, operation at normal carbide speeds may not be practical because the high cobalt binder level in these materials significantly reduces their resistance to cratering.

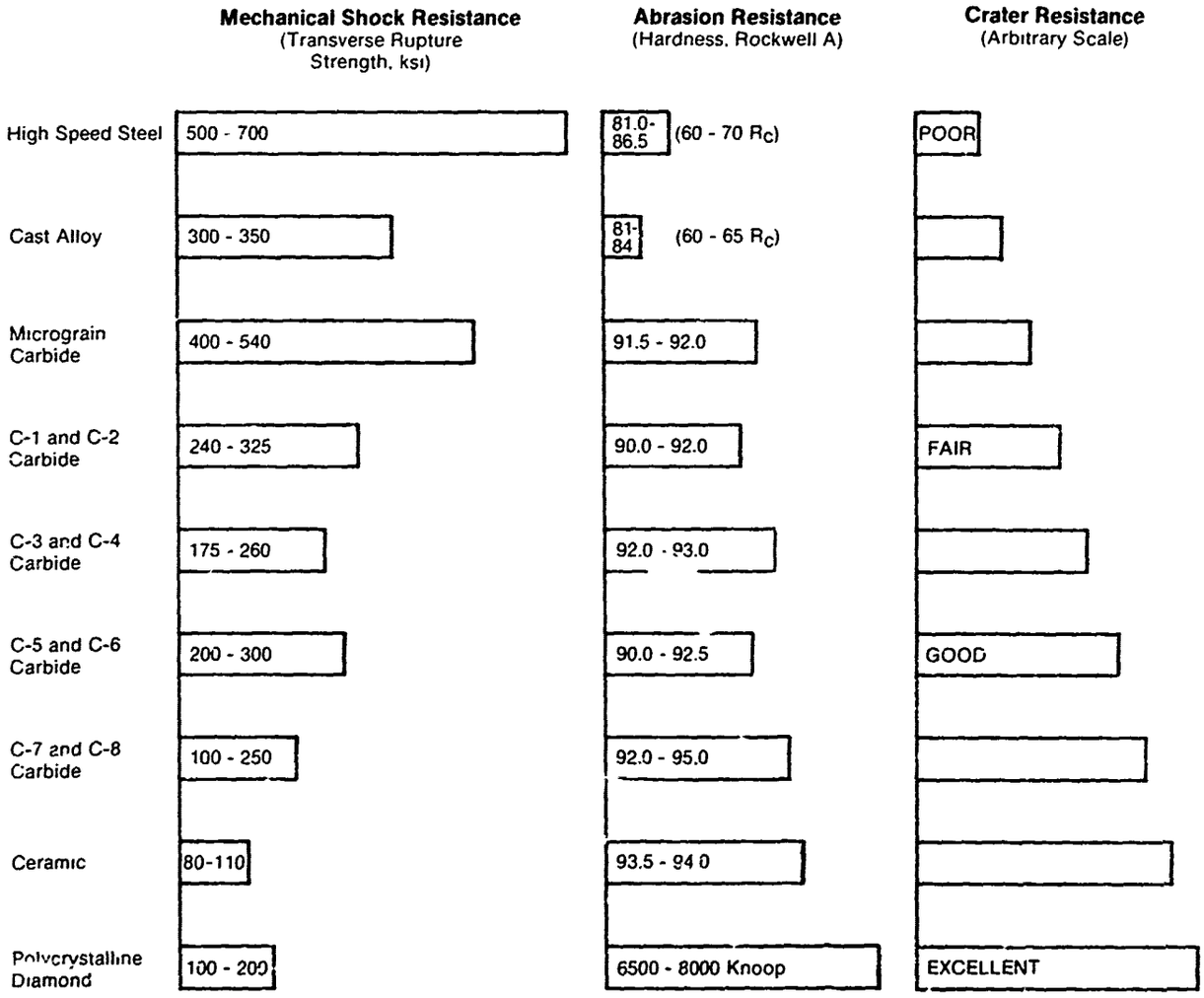


Figure 14-1 Comparative properties of tool materials derived from published data for available grades. Crater resistance refers to ferrous metals.

14 TOOL MATERIALS

14.6 Coated Carbides

Perhaps the most important advance in cutting tool technology during the past decade has been the development of coated carbide inserts. The impact of this improvement can be measured in terms of the major benefits of increased metal removal rate and tool life that have been found in turning and face milling of cast irons and steels. These two general types of work materials still represent the bulk of the work material being machined in the United States. The application of these tool materials overlaps much of the entire C-1 through C-8 range. The coatings are usually, but not necessarily, deposited on conventional carbide inserts. Special substrates are being developed which definitely are not suitable as metal cutting tools without the coatings.

Titanium carbide coatings are produced by reactive deposition from the gaseous phase, where titanium tetrachloride vapor is converted to fine grain titanium crystals. The process continues until the coating is about 0.0002-inch (5 μm) thick. Other coatings such as TiN, HfN, HfC, and Al_2O_3 are produced using the same technology with other gaseous components.

The improved machining performance of coated carbide inserts results from reduced friction, increased surface hardness and, most important of all, chemical inertness. The thin layer of coating provides a cobalt-free diffusion barrier between the workpiece and the insert. The reduction or elimination of diffusion results in an appropriate reduction of cratering and flank wear. For many applications, this results in either a longer tool life or a higher metal removal rate when compared to uncoated carbides. An exception to this advantage would probably occur in highly abrasive, lower cutting speed operations. Newer grades are being developed to successfully perform heavy roughing and interrupted cuts.

14.7 Ceramic Tool Materials

There are two main types of ceramic cutting tools, the pure alumina tools and the alloyed cermets (see table 14-8). The cermets are also aluminum-oxide-base materials containing various amounts of titanium carbide or other alloying ingredients The alumina tools are white in appearance. Although these tools may be either hot pressed or cold pressed, they are usually cold pressed. The alumina inserts are normally applied in lighter-duty cuts, such as noninterrupted turning and boring.

TABLE 14-8 Ceramic Inserts

IDENTIFICATION	MANUFACTURER
TRW-138 TRW-1322	TRW Wendt-Sonis, Rogers, AR
VR-97 VR-100*	Fansteel, VR/Wesson Div., Waukegan, IL
Ceratip 30 Ceratip 42. Cermet 61*	Ceratip—Division of Kyocera International Inc., San Diego, CA
C1	NTK Division of NGK Spark Plug Co. Ltd , Harbor City, CA
GEM9 GEM1 GEM2* GEM3*	Greenleaf Corporation, Saegertown, PA
K 090* K 060	Kennametal Inc., Latrobe, PA
V-32* V-34	Valenite Div., Valeron Corp., Detroit, MI
G-10* G-20	Babcock & Wilcox, Rochester, MI
CA-W CA-B*	Carmet Company, Madison Heights, MI

NOTE Listings do not necessarily imply equivalency of various manufacturers grades This chart is not to be considered an endorsement of or an approved list of any manufacturer's products.

*Cermet

The cermet tools are hot pressed. These tools are much tougher than the alumina inserts and are therefore applicable for roughing, for interrupted cuts, for some face milling and for machining materials of very high hardness (60 to 68 R_C).

Presently, the main uses for ceramic tool materials are in finish and semifinish turning. Typical applications are boring and facing of cast irons for the automotive industry, turning of steels for ordnance applications, and finish turning and facing of chilled iron and of hardened steel rolls. Where high rigidity has been designed into the machine tool and the tooling, roughing of cast iron and steel may be performed with ceramic materials.

In addition to the introduction of hot-pressed cermets, three recent developments in the preparation of ceramic inserts have expanded the usage of these tools. Those developments are as follows:

1. The grinding of K-lands on the cutting edges
2. The use of thicker inserts
3. The use of larger nose radii

The primary failure mode of ceramic inserts has always been either edge chipping or insert breakage. These three improvements have all helped reduce those problems.

A "K-land" is a precision-ground flat that removes the sharp cutting edge where the top and side faces of the insert intersect. The width of the flat varies from 0.002 to 0.012 inch [0.05 to 0.30 mm]. The angle of the bevel may vary from 30 to 45 degrees with respect to the top face.

A thicker insert will be less likely to break under the increased cutting forces produced by a chipped cutting edge. This increases insert life by preserving unused corners which would normally be lost if the insert cracks.

A larger nose radius will naturally present a stronger corner than will a smaller radius. This also helps to reduce edge chipping and nose breakage.

Even with the improved technology of adding K-lands and using thicker inserts, more care must be exercised in applying ceramic tools than is : mally used in applying high speed steel or carbide inserts. In particular, it is necessary to avoid mechanical shock where possible and thermal shock at all times. Ceramic tools are rarely, if ever, used with cutting fluids. Their application in turning, boring or milling is always dry. Negative rake inserts are used almost exclusively.

14 TOOL MATERIALS

14.8 Diamond Tools

Diamond tools are most generally used for machining nonferrous alloys and abrasive materials, such as presintered carbides and ceramics, graphite, fiberglass, rubber and high-silicon aluminum alloys. Man-made polycrystalline diamonds that are sintered under very high temperatures and pressures are now available as cutting tool inserts of various sizes and shapes. Manufacturers of these tools are listed in table 14-9. Polycrystalline diamond tools have proved to be, in most cases, greatly superior to natural mined diamonds in normal machining operations on the work materials listed above. However, even though the polycrystalline diamonds are much tougher and able to withstand a great deal more abuse than natural mined diamonds, it is still good practice to observe as much care in handling the tools as possible. If natural mined diamonds are desired for use as the cutting tool material, then the following guidelines should be observed:

Diamond tools are purchased from suppliers who are expert in the art of cutting and orienting diamonds and should be returned to them for resharpening. In-house grinding or reshaping should not be attempted. The diamond tool should be resharpened as soon as it becomes dull to minimize breakage, thereby increasing the number of possible resharpenings.

TABLE 14-9 Producers of Polycrystalline Diamond Tools

Carboloy Division of General Electric Company Detroit, MI
Kennametal Inc. Latrobe, PA
Megadiamond Industries Chicago, IL

In general, diamond tools should be treated with the same care as would be used with any very hard, brittle tool material. However, even light interrupted cuts are possible with the stronger polycrystalline diamonds. Diamond tools are generally used with positive-rake tool geometry in order to reduce the forces on the tool, but there are other applications of negative-rake geometries that have proved successful. The new strength and reduced cost of polycrystalline diamond have opened up many new fields of machining, and new applications continue to be found.

The use of a cutting fluid will usually increase the tool life of the diamond, but where this is not practical, a stream of air can be used to cool the tool and keep the cutting edge free from chips.

SECTION 15

TOOL GEOMETRY

TOOL GEOMETRY GUIDELINES

The following tables show the range of standard tool geometries that are used for various work materials. Negative rake is shown wherever applicable because it provides a stronger cutting edge and usually better tool life on roughing operations.

Standard "off-the-shelf" tools are satisfactory for most applications.

"Modified" standard tools for specific materials are offered by many tool manufacturers at costs considerably less than for special tools.

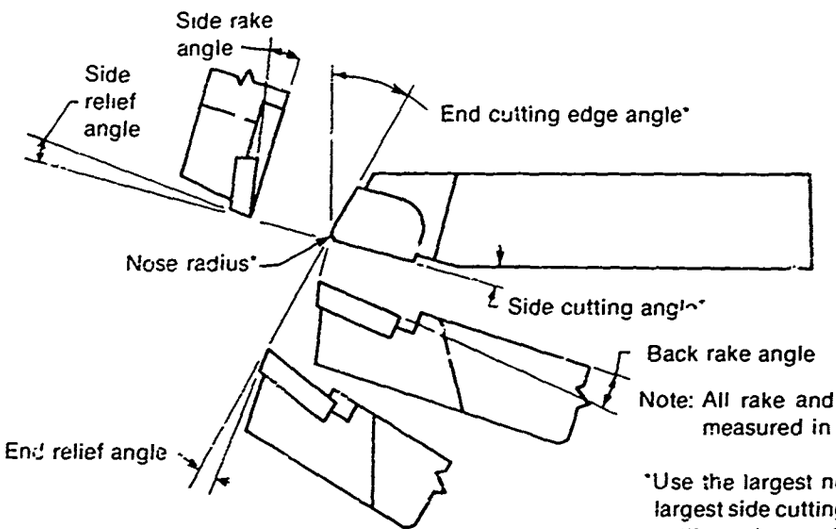
Special tools may be justified for high-production applications or for the machining of complex parts or difficult-to-machine alloys.

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15.1 Turning and Boring Tools, Single Point

TOOL GEOMETRY



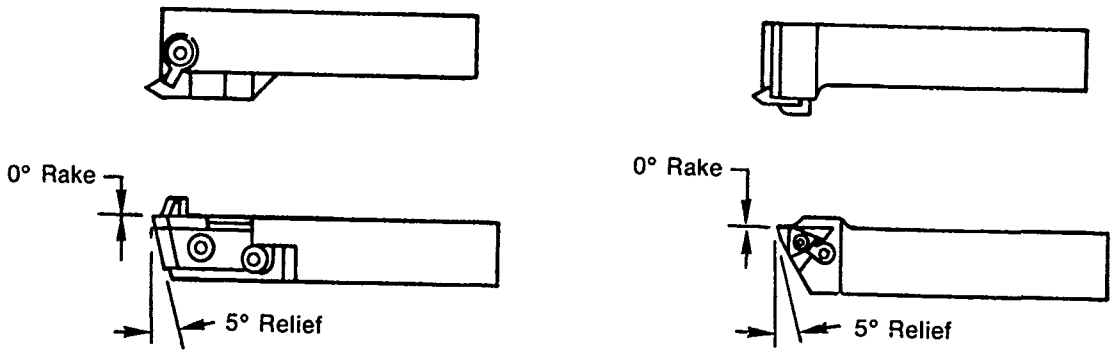
Note: All rake and relief angles are measured in normal direction.

*Use the largest nose radius and the largest side cutting edge angle or end cutting edge angle that are consistent with part requirements.

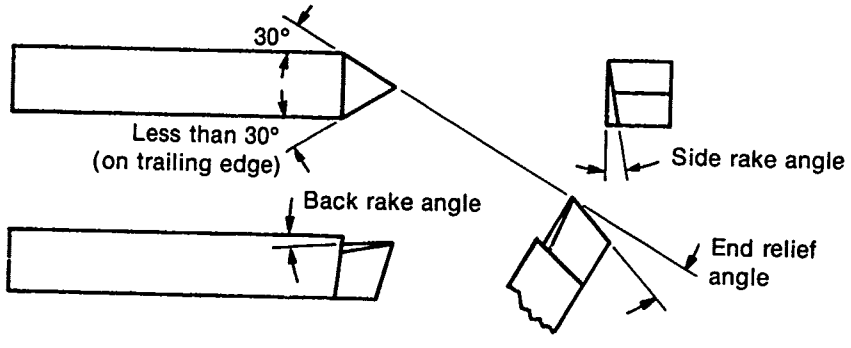
MATERIAL	HARDNESS Bhn	HIGH SPEED STEEL				CARBIDE					
						BRAZED			INDEXABLE		
		Back Rake Angle degrees	Side Rake Angle degrees	End Relief Angle degrees	Side Relief Angle degrees	Back Rake Angle degrees	Side Rake Angle degrees	Relief Angles degrees	Back Rake Angle degrees	Side Rake Angle degrees	Relief Angles degrees
Free Machining Carbon Steels-Wrought	85-225	10	12	5	5	0	6	7	0	5	5
Carbon Steels-Wrought and Cast	225-325	8	10	5	5	0	6	7	0	5	5
Free Machining Alloy Steels-Wrought	325-52R_c	0	10	5	5	0	6	7	-5	-5	5
Alloy Steels-Wrought and Cast High Strength Steels-Wrought Maraging Steels-Wrought Tool Steels-Wrought Nitriding Steels-Wrought Armor Plate-Wrought Structural Steels-Wrought	52R_c-58R_c	—	—	—	—	—	—	—	-5	-5	5
Free Machining Stainless Steels-Wrought	135-275	5	8	5	5	0	6	7	-5	5	5
	275-425	0	10	5	5	0	6	7	-5	-5	5
Stainless Steels, Ferritic-Wrought and Cast	135-185	5	8	5	5	0	6	7	0	5	5
Stainless Steels, Austenitic-Wrought and Cast	135-275	0	10	5	5	0	6	7	0	5	5
Stainless Steels, Martensitic-Wrought and Cast	135-325	0	10	5	5	0	6	7	0	5	5
	325-425 48R_c-52R_c	0	10	5	5	0	6	7	-5	-5	5

MATERIAL	HARDNESS Bhn	HIGH SPEED STEEL				CARBIDE					
						BRAZED			INDEXABLE		
		Back Rake Angle degrees	Side Rake Angle degrees	End Relief Angle degrees	Side Relief Angle degrees	Back Rake Angle degrees	Side Rake Angle degrees	Relief Angles degrees	Back Rake Angle degrees	Side Rake Angle degrees	Relief Angles degrees
Precipitation Hardening Stainless Steels-Wrought and Cast	150-450	0	10	5	5	0	6	7	-5	-5	5
Gray Cast Irons Ductile Cast Irons Malleable Cast Irons Compacted Graphite Cast Irons White Cast Irons	100-200	5	10	5	5	0	6	7	-5	-5	5
	200-300	5	8	5	5	0	6	7	-5	-5	5
	300-400	5	5	5	5	-5	-5	7	-5	-5	5
Aluminum Alloys-Wrought and Cast	30-150 500 kg	20	15	12	10	3	15	7	0	5	5
Magnesium Alloys-Wrought and Cast	40-90 500 kg	20	15	12	10	3	15	7	0	5	5
Titanium Alloys-Wrought and Cast	110-440	0	5	5	5	0	6	7	-5	-5	5
Copper Alloys-Wrought and Cast	40-200 500 kg	5	10	8	8	0	8	7	0	5	5
Nickel Alloys-Wrought and Cast Chrome-Nic Alloys Beryllium-Nickel Alloys	80-360	8	10	12	12	0	6	7	-5	-5	5
Nitinol Alloys-Wrought	210-340 $40R_c$-$52R_c$	-	-	-	-	0	5	7	0	5	5
High Temperature Alloys-Wrought and Cast	140-475	0	10	5	5	0	6	7	5	0	5
Columbium Alloys-Wrought, Cast, P/M Molybdenum Alloys-Wrought, Cast, P/M Tantalum Alloys-Wrought, Cast, P/M	170-290	0	20	5	5	0	20	7	-	-	5
Tungsten Alloys-Wrought, Cast, P/M	180-320	-	-	-	-	-15	0	7	-	-	-
Zinc Alloys-Cast	80-100	10	10	12	4	5	5	7	0	5	5
Uranium Alloys-Wrought	190-210	-	-	-	-	0	0	7	-5	0	7
Zirconium Alloys-Wrought	140-280	15	10	10	10	5	5	7	5	5	6
Thermoplastics	All	0	0	20 to 30	15 to 20	0	0	20 to 30	0	0	20 to 30
Thermosetting Plastics	All	0	0	20 to 30	15 to 20	0	15	7	0	15	5
Magnetic Alloys, Nickel- and Cobalt-Base Controlled Expansion Alloys	125-250	10	8	8	8	-	-	-	-	-	-
Powder Metal Alloys — Copper	All	10	8	8	8	6	12	7	-	-	-
Powder Metal Alloys — Iron	All	0	0	8	8	6	16	7	0	0	5
Magnetic Core Iron	185-240	15	30	8	8	20	0	7	5	5	5
Carbon and Graphite	All	0	0	20	20	0	0	20	0	0	15
Machinable Carbide (Ferro-Tic)	$40R_c$-$51R_c$	-5	-5	5	5	-5	-5	7	-5	-5	5
Machinable Glass Ceramic	250 Knoop 100 g	0	15	5	5	1	0	7	0	0	5

15.2 Threading Tools, Single Point
TOOL GEOMETRY



Typical Carbide Threading Tools



Typical High Speed Steel Threading Tool

MATERIAL		HARDNESS Bhn	HIGH SPEED STEEL Back Rake Angle degrees	Side Rake Angle degrees	End Relief Angle degrees
Free Machining Carbon Steels-Wrought Carbon Steels-Wrought and Cast Free Machining Alloy Steels-Wrought Alloy Steels-Wrought and Cast High Strength Steels-Wrought Maraging Steels-Wrought Tool Steels-Wrought Nitriding Steels-Wrought Armor Plate-Wrought Structural Steels-Wrought		80-225	10 to 15	10 to 15	5 to 10
		225-325	8 to 12	8 to 12	5 to 10
		325-425	0 to 5	5 to 10	5 to 10
Free Machining Stainless Steels-Wrought		135-275	5 to 10	5 to 8	5 to 10
		275-425	0 to 5	10 to 15	5 to 10
Stainless Steels, Ferritic-Wrought and Cast		135-185	5 to 10	5 to 8	5 to 10
Stainless Steels, Austenitic-Wrought and Cast		135-275	0 to 5	10 to 15	5 to 10
Stainless Steels, Martensitic and Precipitation Hardening-Wrought and Cast		135-425	0 to 5	10 to 15	3 to 10
Gray, Ductile and Malleable Cast Irons Compacted Graphite Cast Irons		100-200	5 to 8	8 to 12	5 to 10
		200-400	0 to 5	5 to 10	5 to 10
Aluminum Alloys-Wrought and Cast		30-150 500 kg	20 to 30	10 to 15	5 to 10
Magnesium Alloys-Wrought and Cast		40-90 500 kg	20 to 30	10 to 15	5 to 10
Titanium Alloys-Wrought and Cast		110-440	0	0 to 5	5 to 15
Copper Alloys-Wrought and Cast*	Group 1	40-200 500 kg	0	5 to 10	5 to 10
	Group 2	40-200 500 kg	3 to 7	5 to 10	5 to 10
	Group 3	40-200 500 kg	7 to 15	5 to 10	5 to 10
Nickel Alloys-Wrought and Cast		80-360	6 to 9	9 to 12	2 to 12
High Temperature Alloys-Wrought and Cast		140-475	0 to 10	10 to 15	5 to 12

*Copper alloy groups.

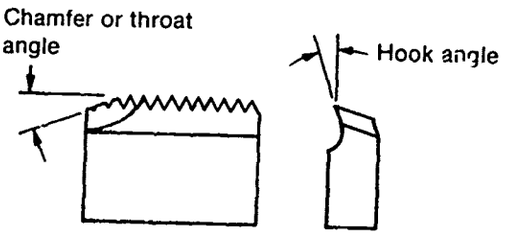
Group 1						
314	356	377	842	858	935	953
330	360	385	844	864	937	954
332	365	485	848	867	938	956
335	366	544	852	879	939	973
340	367	834	854	928	943	974
342	368	836	855	932	944	976
353	370	838	857	934	945	978

Group 2						
226	442	467	821	872	915	948
230	443	651	833	874	922	952
240	444	655	853	875	923	955
260	445	675	861	876	925	957
268	464	687	862	878	926	958
270	465	770	865	903	927	
280	466	817	868	905	947	

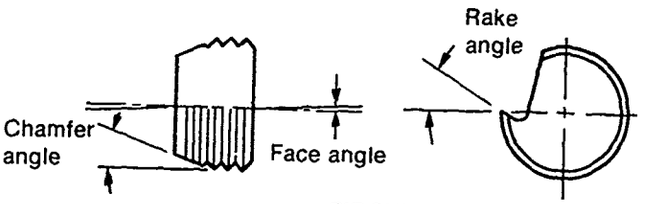
Group 3						
102	172	614	803	818	863	917
110	175	706	805	820	902	962
113	210	715	807	822	907	963
114	220	745	809	824	909	964
115	505	752	811	825	910	966
116	510	754	813	826	911	
122	521	757	814	827	913	
170	524	801	815	828	916	

15.3 Die Threading Tools, Die Chasers

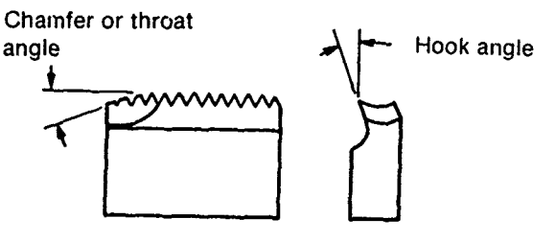
TOOL GEOMETRY



Milled

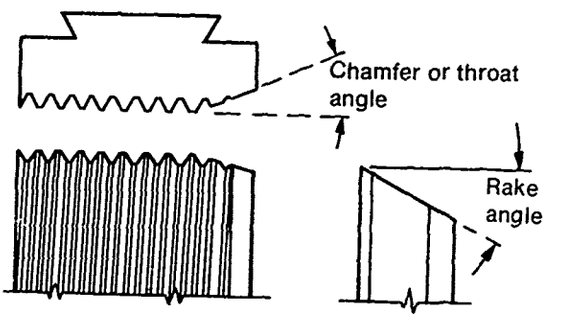


CIRCULAR



Hobbed or Tapped

RADIAL

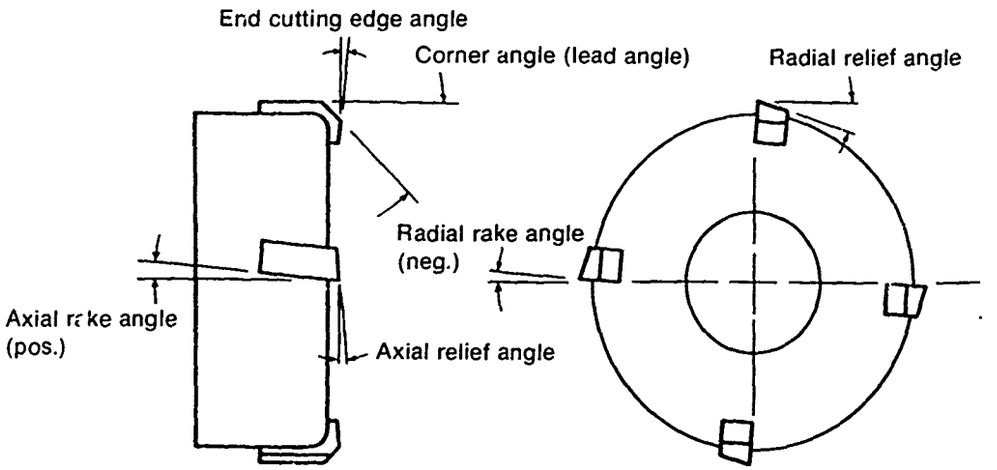


TANGENT

MATERIAL		HARDNESS Bhn	HIGH SPEED STEEL					CARBIDE
			CIRCULAR		TANGENT	RADIAL		RADIAL
						TAPPED	MILLED	
			Rake Angle degrees	Face Angle degrees	Rake Angle degrees	Rake Angle degrees	Rake Angle degrees	Rake Angle degrees
Free Machining Carbon Steels-Wrought Carbon Steels-Wrought and Cast Free Machining Alloy Steels-Wrought Alloy Steels-Wrought and Cast High Strength Steels-Wrought Maraging Steels-Wrought Tool Steels-Wrought Nitriding Steels-Wrought Armor Plate-Wrought Structural Steels-Wrought		100-330	20	1-1/2	15 to 25	10 to 15	10 to 15	5 to 10
		85-225	20	1-1/2	25 to 35	8 to 15	8 to 15	5 to 10
		225-330	20	1-1/2	18 to 22	5 to 7	5 to 7	0 to 5
Free Machining Stainless Steels-Wrought		135-330	15 to 25	1-1/2	10 to 20	7 to 10	7 to 10	5 to 10
Stainless Steels, Ferritic-Wrought and Cast		135-185	20 to 25	1-1/2	20 to 28	10 to 15	10 to 12	5 to 10
Stainless Steels, Austenitic-Wrought and Cast		135-275	25 to 30	1-1/2	15 to 20	10 to 12	10 to 15	5 to 10
Stainless Steels, Martensitic-Wrought and Cast		135-200	15 to 20	1-1/2	20 to 28	10 to 12	7 to 10	5 to 10
		200-325	15 to 20	1-1/2	15 to 20	10 to 12	7 to 10	5 to 10
Gray Cast Irons Compacted Graphite Cast Irons		110-330	10	2	15 to 25	0 to 5	0 to 5	0 to 5
Ductile and Malleable Cast Irons		110-330	10	1-1/2	18	7 to 10	7 to 10	5 to 10
Aluminum Alloys-Wrought and Cast		30-150 500 kg	20 to 25	2	20 to 35	15 to 25	15 to 25	10 to 15
Magnesium Alloys-Wrought and Cast		40-90 500 kg	20 to 25	2	20 to 35	15	15	10
Titanium Alloys-Wrought and Cast		110-340	5 to 20	0 to 1	5 to 20	0 to 10	0 to 10	5 to 10
Copper Alloys-Wrought and Cast*	Group 1	40-200 500 kg	-5 to 5	0	0 to 10	0 to-10	0 to -10	0 to 5
	Group 2	40-200 500 kg	10 to 20	1 to 2	20 to 25	0 to 10	0 to 10	0 to 5
	Group 3	40-200 500 kg	15 to 35	2 to 3	30 to 35	12 to 30	12 to 30	5 to 15
Nickel Alloys-Wrought and Cast		80-240	15 to 25	1 to 2	20 to 25	20 to 30	20 to 30	5 to 15
		240-320	10 to 20	1 to 2	15 to 20	8 to 15	8 to 15	5 to 10
High Temperature Alloys-Wrought and Cast		180-230	15 to 20	1 to 2	20 to 25	15 to 25	15 to 25	10 to 15
		230-320	5 to 15	1 to 2	15 to 20	10 to 15	10 to 15	10
Zinc Alloys-Cast		80-100	15 to 20	1 to 2	5	10 to 15	10 to 15	10
Thermoplastics		$31R_R$-$103R_M$	5 to 10	0	5 to 10	0 to 5	0 to 5	5

*See section 15.2 for copper alloy groups.

15.4 Face Mills
TOOL GEOMETRY

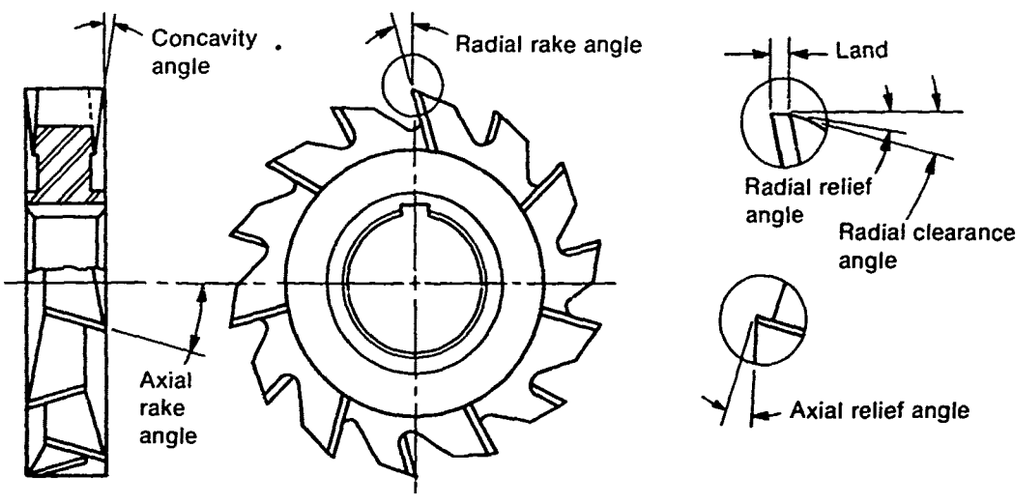


MATERIAL	HARDNESS Bhn	HIGH SPEED STEEL		INDEXABLE CARBIDE		BRAZED CARBIDE		CORNER ANGLE degrees	END CUTTING EDGE ANGLE degrees	AXIAL RELIEF ANGLE degrees	RADIAL RELIEF ANGLE degrees
		Axial Rake Angle degrees	Radial Rake Angle degrees	Axial Rake Angle degrees	Radial Rake Angle degrees	Axial Rake Angle degrees	Radial Rake Angle degrees				
Free Machining Carbon Steels and Carbon Steels-Wrought and Cast Free Machining Alloy Steels and Alloy Steels-Wrought and Cast Maraging Steels-Wrought Tool Steels-Wrought Structural Steels-Wrought	85-270	10 to 15	10 to 15	5 to 7	-5 to -14	0 to -7	0 to -7	30	5 to 10	5 to 7	3 to 7
	270-325	10 to 15	10 to 15	-4 to -8	-3 to -11	0 to -7	0 to -7	30	5 to 10	5 to 7	3 to 7
	325-425	10 to 12	10 to 12	-4 to -8	-3 to -11	0 to -10	0 to -10	30	5 to 10	5 to 7	3 to 7
	43R_c-50R_c	5 to 10	5 to 10	-4 to -8	-3 to -11	-5 to -15	-5 to -15	45	4 to 7	5 to 7	3 to 7
	50R_c-56R_c	-	-	-4 to -8	-3 to -11	-5 to -15	-5 to -15	45	4 to 7	8	8
High Strength Steels-Wrought	225-425	5 to 10	0 to 10	-4 to -8	-3 to -11	-5 to -15	-5 to -15	45	4 to 7	5 to 7	3 to 7
	45R_c-58R_c	-	-	-4 to -8	-3 to -11	-5 to -15	-5 to -15	45	4 to 7	8	8
Nitriding Steels-Wrought	200-350	5 to 10	5 to 10	-4 to -8	-3 to -11	0 to -10	-5 to -15	45	5 to 10	5 to 7	3 to 5
Armor Plate-Wrought	250-320	0 to 5	0 to 5	-4 to -8	-3 to -11	0 to -10	-5 to -15	45	4 to 7	5 to 7	3 to 5
Free Machining Stainless Steels-Wrought	135-275	10 to 15	10 to 12	5 to 11	-5 to -11	0	0 to 5	45	5	8 to 10	8 to 10
	275-425	5 to 10	5 to 10	5 to 11	-5 to -11	0	0 to -5	45	5	8 to 10	8 to 10

MATERIAL	HARDNESS Bhn	HIGH SPEED STEEL		INDEXABLE CARBIDE		BRAZED CARBIDE		CORNER ANGLE	END CUTTING EDGE ANGLE	AXIAL RELIEF ANGLE	RADIAL RELIEF ANGLE
		Axial Rake Angle degrees	Radial Rake Angle degrees	Axial Rake Angle degrees	Radial Rake Angle degrees	Axial Rake Angle degrees	Radial Rake Angle degrees	degrees	degrees	degrees	degrees
Stainless Steels, Ferritic and Austenitic-Wrought and Cast	135-275	10 to 15	10 to 12	5 to 11	-5 to -11	0 to 5	0 to -5	45	5	8 to 10	8 to 10
Stainless Steels, Martensitic-Wrought and Cast	135-425	5 to 10	5 to 10	5 to 11	-5 to -11	0	0 to -5	45	5	8 to 10	8 to 10
Precipitation Hardening Stainless Steels-Wrought and Cast	150-450	5 to 10	5 to 10	5 to 7	0 to 5	0	0	45	5	8 to 10	8 to 10
Gray Cast Irons Ductile Cast Irons Malleable Cast Irons Compacted Graphite Cast Irons White Cast Irons	100-400	20 to 30	-5 to -10	5 to 11	-5 to -11	5 to 10	5 to -10	45	5 to 10	4 to 7	4 to 7
Aluminum Alloys-Wrought and Cast	30-150 500 kg	20 to 35	20 to 35	5 to 7	0 to 5	10 to 20	10 to 20	45	7 to 12	3 to 5	10 to 12
Magnesium Alloys-Wrought and Cast	40-90 500 kg	20 to 35	20 to 35	5 to 7	0 to 5	10 to 20	10 to 20	45	7 to 12	3 to 5	10 to 12
Titanium Alloys-Wrought and Cast	110-440	5	5	0 to -5	0 to -5	0 to -5	-10	45	6 to 12	10 to 12	10 to 12
Copper Alloys-Wrought and Cast	40-200 500 kg	12 to 25	10 to 12	5 to 7	0 to 5	3 to 10	3 to 10	45	7 to 12	3 to 5	5 to 10
Nickel Alloys, Chrome-Nickel & Beryllium-Nickel Alloys-Wrought & Cast	80-360	7	15	5 to 11	-5 to -14	5 to 10	0 to -5	45	5	7 to 9	7 to 9
Nitinol Alloys-Wrought	210-340 $48R_c$-$60R_c$	-	-	5 to 7	0 to 5	0	0	45	10	12	12
High Temperature Alloys-Wrought and Cast	200-475	5 to 10	5 to 10	0 to 5	0 to -5	0 to 5	0 to -5	45	5	7 to 10	7 to 10
Columbium Alloys-Wrought, Cast, P/M	170-225	0	20	5 to 7	0 to 5	0	10	45	5 to 10	10	10
Molybdenum Alloys-Wrought, Cast, P/M	220-290	0	20	5 to 7	0 to 5	0	0	45	5 to 10	10	10
Tantalum Alloys-Wrought, Cast, P/M	200-250	0	20	5 to 7	0 to 5	0	0	45	5 to 10	10	10
Tungsten Alloys-Wrought, Cast, P/M	180-320	-	-	-4 to -8	-3 to -11	-15	0	45	5 to 10	15	15
Zinc Alloys-Cast	80-100	10 to 15	10 to 15	5 to 7	0 to 5	10 to 12	10 to 12	45	7 to 12	10	10 to 12

15.5 Side and Slot Mills—Arbor Mounted

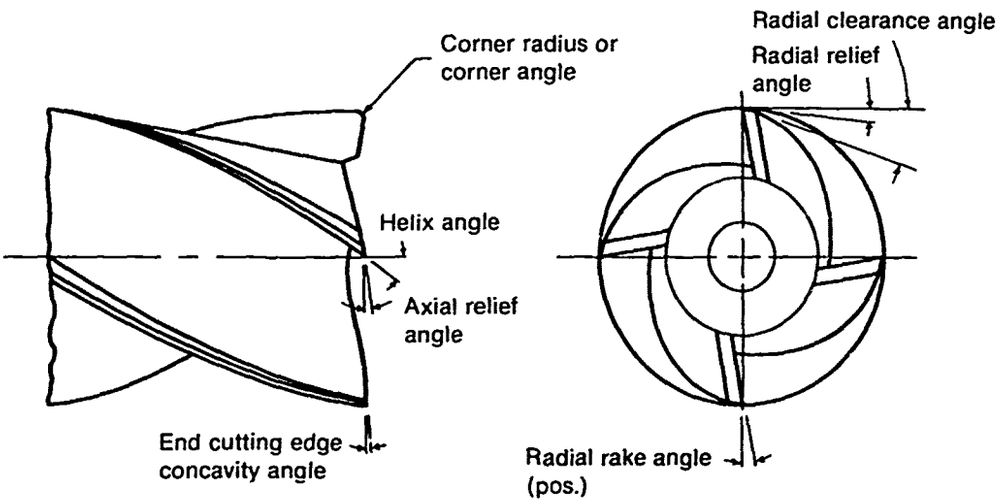
TOOL GEOMETRY



MATERIAL	HARDNESS	HIGH SPEED STEEL				CARBIDE			
		Axial Rake Angle	Radial Rake Angle	Axial Relief Angle	Radial Relief Angle	Axial Rake Angle	Radial Rake Angle	Axial Relief Angle	Radial Relief Angle
	Bhn	degrees	degrees	degrees	degrees	degrees	degrees	degrees	degrees
Free Machining Carbon Steels-Wrought Carbon Steels-Wrought and Cast Free Machining Alloy Steels-Wrought	85-325	10 to 15	10 to 15	3 to 5	4 to 8	0 to -5	-5 to 5	2 to 4	5 to 8
	325-425	10 to 12	5 to 12	3 to 5	4 to 8	0 to -5	-5 to 5	2 to 4	5 to 8
	45R_c-52R_c	10 to 12	5 to 12	2 to 4	3 to 7	-5 to -10	0 to -10	2 to 4	5 to 8
Alloy Steels-Wrought and Cast	125-425	10 to 12	5 to 12	3 to 5	4 to 8	-5 to -10	0 to -10	2 to 5	5 to 8
	45R_c-52R_c	10 to 12	5 to 12	2 to 4	3 to 7	-5 to -10	0 to -10	2 to 4	3 to 6
High Strength Steels, Maraging Steels and Tool Steels-Wrought	100-52R_c	10 to 12	5 to 12	2 to 4	3 to 7	-5 to -10	0 to -10	2 to 4	5 to 8
Nitriding Steels-Wrought	200-350	10 to 12	5 to 12	2 to 4	3 to 7	-5 to -10	0 to -10	2 to 4	3 to 6
Armor Plate-Wrought	250-320	0 to 5	0 to 5	2 to 4	3 to 7	-5 to -10	-5 to -10	2 to 4	3 to 6
Structural Steels-Wrought	100-50R_c	10 to 12	5 to 12	3 to 5	4 to 8	0 to -5	0 to -10	2 to 4	5 to 8
Free Machining Stainless Steels-Wrought	135-425	10 to 12	5 to 12	3 to 5	4 to 8	0 to 5	-5 to 5	2 to 4	5 to 8
Stainless Steels, Ferritic-Wrought and Cast Stainless Steels, Austenitic-Wrought and Cast	135-52R_c	10 to 12	5 to 12	3 to 5	4 to 8	0 to 5	-5 to 5	2 to 4	5 to 8
Stainless Steels, Martensitic-Wrought and Cast	135-52R_c	10 to 12	5 to 12	2 to 4	3 to 7	-5 to -10	0 to -10	2 to 4	5 to 8
Precipitation Hardening Stainless Steels-Wrought and Cast	150-450	10 to 12	5 to 12	2 to 4	4 to 8	0 to -5	0 to -10	2 to 4	5 to 8
Gray Cast Irons Ductile Cast Irons Malleable Cast Irons	100-400	10 to 12	10 to 12	2 to 4	3 to 7	0 to -10	5 to -10	3 to 5	5 to 8
Aluminum Alloys-Wrought and Cast	30-150 500 kg	12 to 25	10 to 20	5 to 7	5 to 11	10 to 20	5 to 15	5 to 7	7 to 10
Magnesium Alloys-Wrought and Cast	40-90 500 kg	12 to 25	10 to 20	5 to 7	5 to 11	10 to 20	5 to 15	5 to 7	7 to 10
Titanium Alloys-Wrought	110-440	10 to 15	5 to 10	5 to 7	5 to 11	0 to -10	0 to -10	5 to 7	5 to 8
Copper Alloys-Wrought and Cast	40-200 500 kg	12 to 25	10 to 20	5 to 7	5 to 11	10 to 20	5 to 10	4 to 7	5 to 8
Nickel Alloys-Wrought and Cast	80-360	10 to 20	10 to 15	3 to 5	4 to 8	-5 to -10	0 to -10	3 to 5	5 to 8
High Temperature Alloys-Wrought and Cast	140-300	10 to 15	10 to 15	1 to 5	5 to 10	-5 to -10	0 to -10	3 to 5	5 to 8
	300-475	10 to 12	5 to 12	1 to 5	4 to 8	-5 to -10	0 to -10	3 to 5	5 to 8
Columbium, Molybdenum Alloys-Wrought, Cast, P/M	170-290	0	15 to 20	3 to 5	5 to 10	0	5 to 15	7 to 10	7 to 10
Tantalum Alloys-Wrought, Cast, P/M	200-250	0	15 to 20	3 to 5	5 to 10	0	5 to 15	7 to 10	7 to 10
Tungsten Alloys-Wrought, Cast, P/M	180-320	-	-	-	-	-10 to -15	5 to 15	10 to 15	10 to 15
Zinc Alloys-Cast	80-100	10 to 20	10 to 20	5 to 7	8 to 11	10 to 15	10 to 15	7 to 10	7 to 10

15.6 End Mills—Peripheral and Slotting, High Speed Steel

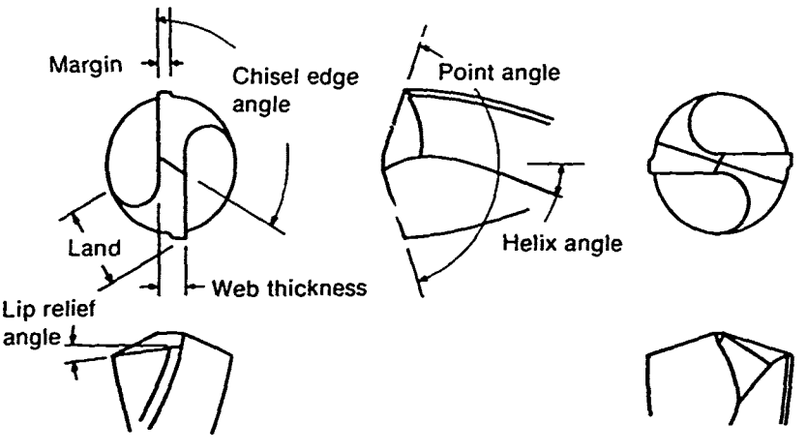
TOOL GEOMETRY



NOMINAL CUTTER DIAMETER	GENERAL PURPOSE—30° to 35° HELIX Steels, Cast Irons, Copper Alloys, Titanium Alloys, Nickel Alloys, High Temperature Alloys and Zinc Alloys			35° to 45° HELIX Aluminum and Magnesium Alloys		
	Radial Primary Relief Angle	Primary Land Width	Radial Secondary Clearance Angle	Radial Primary Relief Angle	Primary Land Width	Radial Secondary Clearance Angle
in	degrees	in	degrees	degrees	in	degrees
1/16	20 to 21	0.007-0.010	30 to 35	20 to 22	0.007-0.010	30 to 35
1/8	12 to 13	0.010-0.015	22 to 28	14 to 18	0.010-0.015	25 to 30
3/16	12 to 13	0.010-0.020	20 to 25	14 to 18	0.010-0.020	25 to 30
1/4	10 to 11	0.010-0.20	20 to 25	12 to 15	0.010-0.020	22 to 28
5/16	10 to 11	0.015-0.025	20 to 25	12 to 14	0.015-0.025	21 to 28
3/8	10 to 11	0.015-0.025	17 to 20	12 to 14	0.015-0.025	19 to 26
7/16	9 to 10	0.020-0.030	17 to 20	11 to 13	0.020-0.030	18 to 25
1/2	9 to 10	0.020-0.030	17 to 20	11 to 13	0.020-0.030	18 to 25
5/8	9 to 10	0.025-0.035	17 to 20	11 to 13	0.025-0.035	18 to 25
3/4	8 to 9	0.030-0.040	15 to 18	10 to 12	0.030-0.040	17 to 24
7/8	8 to 9	0.030-0.040	15 to 18	10 to 12	0.030-0.040	17 to 24
1	8 to 9	0.035-0.050	15 to 18	10 to 12	0.035-0.050	16 to 23
1-1/4	7 to 8	0.040-0.060	13 to 18	9 to 11	0.040-0.060	14 to 22
1-1/2	7 to 8	0.040-0.060	11 to 17	9 to 11	0.040-0.060	13 to 21
1-3/4	7 to 8	0.040-0.060	10 to 16	8 to 10	0.040-0.060	12 to 20
2	6 to 7	0.040-0.060	9 to 15	8 to 10	0.040-0.060	12 to 20
mm	degrees	mm	degrees	degrees	mm	degrees
M1.6	20 to 21	0.200-0.250	30 to 35	20 to 22	0.200-0.250	30 to 35
M3	14 to 15	0.250-0.350	24 to 30	15 to 20	0.250-0.350	25 to 30
M4	12 to 13	0.250-0.400	22 to 28	14 to 18	0.250-0.400	25 to 30
M6	10 to 11	0.250-0.500	20 to 25	12 to 15	0.250-0.500	22 to 28
M7	10 to 11	0.250-0.500	20 to 25	12 to 15	0.250-0.500	22 to 28
M8	10 to 11	0.400-0.650	20 to 25	12 to 14	0.400-0.650	19 to 26
M10	10 to 11	0.400-0.650	17 to 20	12 to 14	0.400-0.650	19 to 26
M12	9 to 10	0.500-0.750	17 to 20	11 to 13	0.500-0.750	18 to 25
M14	9 to 10	0.500-0.750	17 to 20	11 to 13	0.500-0.750	18 to 25
M16	9 to 10	0.650-0.900	17 to 20	11 to 13	0.650-0.900	18 to 25
M20	8 to 9	0.750-1.000	15 to 18	10 to 12	0.750-1.000	17 to 24
M22	8 to 9	0.75-1.000	15 to 18	10 to 12	0.75-1.000	17 to 24
M25	8 to 9	0.900-1.250	15 to 16	10 to 12	0.900-1.250	16 to 23
M32	7 to 8	1.000-1.500	13 to 18	9 to 11	1.000-1.500	13 to 22
M40	7 to 8	1.000-1.500	11 to 17	9 to 11	1.000-1.500	13 to 21
M45	7 to 8	1.000-1.500	10 to 16	8 to 10	1.000-1.500	12 to 20

15.7 Drills, High Speed Steel Twist

TOOL GEOMETRY



MATERIAL	HARDNESS Bhn	DRILL TYPE	POINT ANGLE* degrees	LIP RELIEF ANGLE‡ degrees	HELIX ANGLE	POINT GRIND
Free Machining Carbon Steels-Wrought Carbon Steels-Wrought, Cast and P/M Free Machining Alloy Steels-Wrought Alloy Steels-Wrought, Cast and P/M Maraging Steels-Wrought Tool Steels-Wrought, Cast and P/M Nitriding Steels-Wrought Armor Plate-Wrought Structural Steels-Wrought	85-225	General Purpose	118	A	Standard	Standard
	225-325	General Purpose	118	A	Standard	Standard
	325-425	General Purpose	118 to 135	B	Standard	Crankshaft
	45R_c-52R_c	Heavy Web	118 to 135	B	Standard	Crankshaft
High Strength Steels-Wrought	175-325 325-52R_c	Heavy Web	118 118 to 135	A B	Standard Standard	Crankshaft
Austenitic Manganese Steels-Cast	150-220	Rail Drill	135	B	Low	Split
Free Machining Stainless Steels-Wrought	135-425	General Purpose	118	A	Standard	Crankshaft
Stainless Steels, Ferritic-Wrought and Cast	135-200	General Purpose	118 to 135	A	Standard	Standard
Stainless Steels, Austenitic-Wrought, Cast and P/M Stainless Steels, Martensitic-Wrought, Cast and P/M	200-325	General Purpose	118 to 135	A	Standard	Crankshaft
Precipitation Hardening Stainless Steels-Wrought and Cast	325-425 48R_c-52R_c	Heavy Web	118 to 135	B	Standard	Crankshaft
Gray Cast Irons Ductile Cast Irons Malleable Cast Irons Compacted Graphite Cast Iron White Cast Iron	110-220	General Purpose	118	A	Standard	Standard
	220-400	Heavy Web	118	A	Standard	Standard

NOTE: Use stub-length drills whenever possible on high strength materials.

*Chisel edge angle: 115° to 135°

‡See chart at end of table on next page.

MATERIAL	HARDNESS Bhn	DRILL TYPE	POINT ANGLE* degrees	LIP RELIEF ANGLE‡ degrees	HELIX ANGLE	POINT GRIND
Aluminum Alloys-Wrought and Cast	30-150 500 kg	Polished Flutes	90 to 118	C	High	Standard
Magnesium Alloys-Wrought and Cast	40-90 500 kg	Polished Flutes	70 to 118	C	High	Standard
Titanium Alloys-Wrought and Cast	110-275	General Purpose	118 to 135	B	Standard	Crankshaft
	275-440	Heavy Web	118 to 135	B	Standard	Crankshaft
Copper Alloys-Wrought, Cast and P/M	40-200 500 kg	Polished Flutes	118	C	Low	Standard
Nickel Alloys-Wrought, Cast and P/M Chromium-Nickel Alloys-Cast	80-360	General Purpose	118	B	Standard	Crankshaft
Nitinol Alloys-Wrought	210-360 $48R_c$-$52R_c$	General Purpose	118	B	Standard	Crankshaft
High Temperature Alloys-Wrought and Cast	140-475	Heavy Web	118 to 135	B	Standard	Crankshaft
Columbium, Molybdenum and Tantalum Alloys-Wrought, Cast, P/M	170-290	General Purpose	118	B	Standard	Standard
Tungsten Alloys (Anviloy)†	290-320	General Purpose	118	B	Standard	Standard
Zinc Alloys-Cast	80-100	General Purpose	118	C	Standard	Standard
Uranium Alloys-Wrought§	190-210	Special Carbide	118	5-8	20°	-5° Land on Drill Lip
Zirconium Alloys-Wrought	140-280	General Purpose	118	A	Standard	Crankshaft
Thermoplastics and Thermosetting Plastics†	All	Special Polished	60 to 90	C	Low	Standard
Magnetic Core Iron	185-240	General Purpose	100 to 118	A	High	Standard
Controlled Expansion Alloys	125-250	General Purpose	118	A	Standard	Crankshaft
Magnetic Alloys (Hi Perm 49, HyMu 80)	185-240	General Purpose	118	A	Standard	Crankshaft
Carbon and Graphite	8-100 Shore	General Purpose	90 to 118	C	Standard	Crankshaft
Machinable Carbide (Ferro-Tic)	$40R_c$-$51R_c$	General Purpose	118	B	Standard	Crankshaft

NOTE: Use stub-length drills whenever possible on high strength materials.

*Chisel edge angle: 115° to 135°

†For both hss and carbide drills.

‡For carbide drills.

§See following chart.

Lip Relief Angles at Periphery	Drill Size							
	#80 to #61	#60 to #41	#40 to #31	1/8 to 1/4	1/4 to 3/8	3/8 to 1/2	1/2 to 3/4	1 inch up
A	24°	21°	18°	16°	14°	12°	10°	8°
B	20°	18°	16°	14°	12°	10°	8°	7°
C	26°	24°	22°	20°	18°	16°	14°	12°

15.8 Oil-Hole or Pressurized-Coolant Drills, High Speed Steel

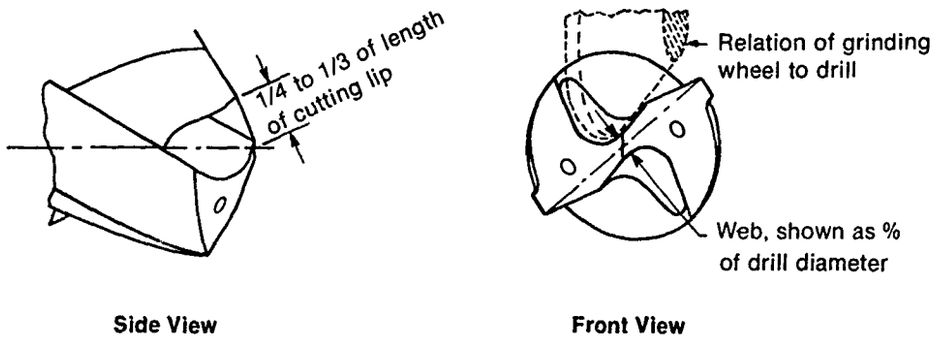
TOOL GEOMETRY

Drill geometry as shown in section 15.7 (HIGH SPEED STEEL TWIST DRILLS) may be used for Oil-Hole or Pressurized-Coolant Drilling.

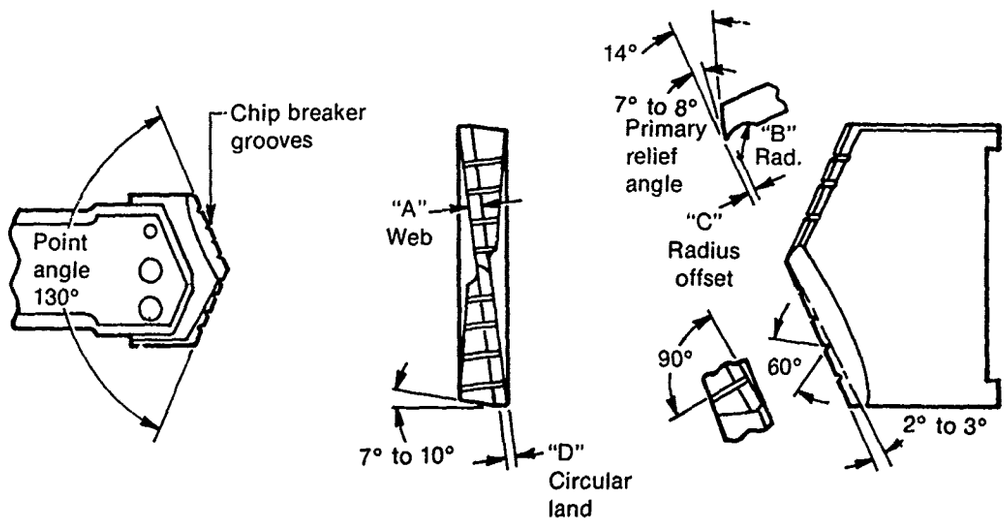
Drills used for Oil-Hole or Pressurized-Coolant Drilling operations, however, have heavy or semi-heavy webs which require thinning of the point. Instructions for thinning are shown below.

DRILL DIAMETER inches	WEB
Up to 1/4	12%
Over 1/4 to 1/2	10%
Over 1/2 to 3/4	8%
Over 3/4 to 1	8%
Over 1 to 1-1/4	7%
Over 1-1/4 to 1-1/2	7%

NOTCH THINNING OF HEAVY WEB OIL-HOLE DRILLS



15.9 Spade Drills, High Speed Steel

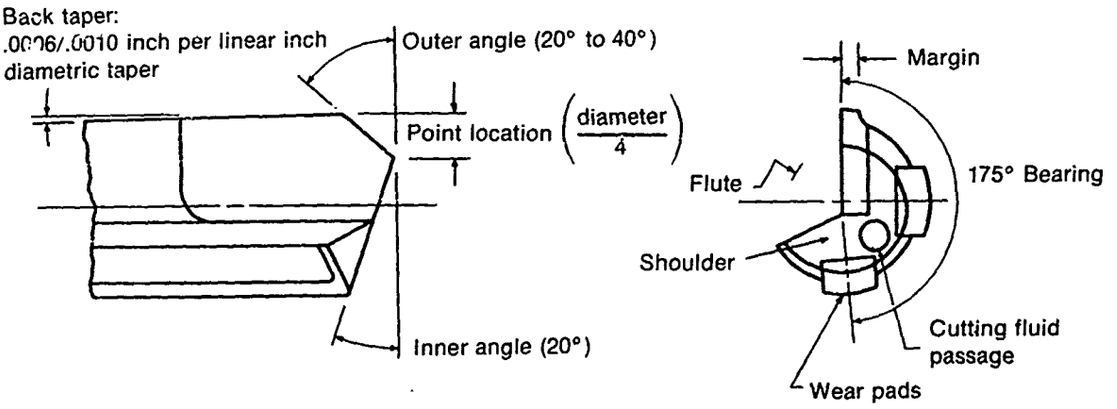


DRILL SIZE RANGE inches	DIMENSIONS	MATERIAL*						
		STEELS, Wrought and Cast and CAST IRONS 100 to 175 Bhn inch	STEELS, Wrought and Cast and CAST IRONS 175 to 330 Bhn inch	STEELS, Wrought and Cast 330 Bhn to 52R_c inch	STAINLESS STEELS, Wrought and Cast inch	ALUMINUM and MAGNESIUM ALLOYS, Wrought and Cast inch	TITANIUM ALLOYS, Wrought and Cast inch	COPPER ALLOYS, Wrought and Cast inch
1-1/32 to 1-1/4	A	1/16	5/64	5/64	1/16	5/64	1/16	5/64
	B	3/16	1/4	1/4	3/16	3/16	1/64 and 10° Rake	5/32
	C	0 to 1/32	0 to 1/32	0 to 1/32	3/64	3/64	1/32	5/64
	D	1/16	1/16	1/16	3/64	1/16	1/16	1/16
1-9/32 to 1-1/2	A	5/64	3/32	5/64	5/64	3/32	5/64	3/32
	B	7/32	9/32	1/4	7/32	1/4	1/64 and 10° Rake	5/32
	C	0 to 1/32	0 to 1/32	0 to 1/32	3/64	1/16	1/32	5/64
	D	5/64	5/64	5/64	3/64	1/16	5/64	5/64
1-9/16 to 2	A	3/32	7/64	3/32	5/64	3/32	3/32	7/64
	B	1/4	5/16	5/16	1/4	5/16	1/64 and 10° Rake	3/16
	C	0 to 1/32	0 to 1/32	0 to 1/32	1/16	5/64	1/32	1/16
	D	5/64	5/64	5/64	1/16	1/16	1/16	5/64
2-1/16 to 2-1/2	A	7/64	1/8	7/64	7/64	7/64	7/64	9/64
	B	9/32	11/32	3/8	9/32	3/8	1/64 and 10° Rake	7/32
	C	0 to 1/32	0 to 1/32	0 to 1/32	1/16	5/32	1/16	7/64
	D	5/64	3/32	5/64	1/16	5/64	5/64	5/64
2-9/16 to 3	A	1/8	9/64	1/8	1/8	7/32	5/32	11/64
	B	9/32	3/8	3/8	5/16	1/2	1/64 and 10° Rake	1/4
	C	0 to 1/32	0 to 1/32	0 to 1/32	5/64	9/32	1/8	7/64
	D	3/32	3/32	3/32	5/64	3/32	3/32	3/32
3-1/16 to 3-1/2	A	5/32	11/64	5/32	5/32	–	–	13/64
	B	5/16	3/8	3/8	11/32	–	–	9/32
	C	0 to 1/32	0 to 1/32	0 to 1/32	3/32	–	–	1/16
	D	7/64	7/64	7/64	5/64	–	–	7/64
3-9/16 to 4	A	11/64	3/16	11/64	11/64	–	–	15/64
	B	5/16	7/16	3/8	3/8	–	–	5/16
	C	0 to 1/32	0 to 1/32	0 to 1/32	7/64	–	–	1/16
	D	1/8	1/8	1/8	3/32	–	–	1/8
4-1/16 to 5	A	3/16	7/32	3/16	3/16	–	–	–
	B	3/8	1/2	1/2	7/16	–	–	–
	C	0 to 1/32	0 to 1/32	0 to 1/32	1/8	–	–	–
	D	5/32	5/32	5/32	3/32	–	–	–

*For other alloys use recommendations for steel as starting geometry.

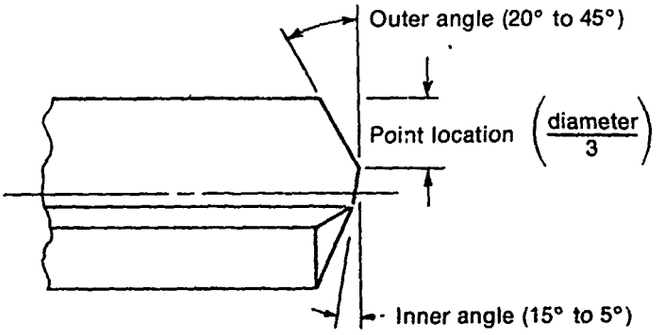
15.10 Gun Drills, Carbide
TOOL GEOMETRY

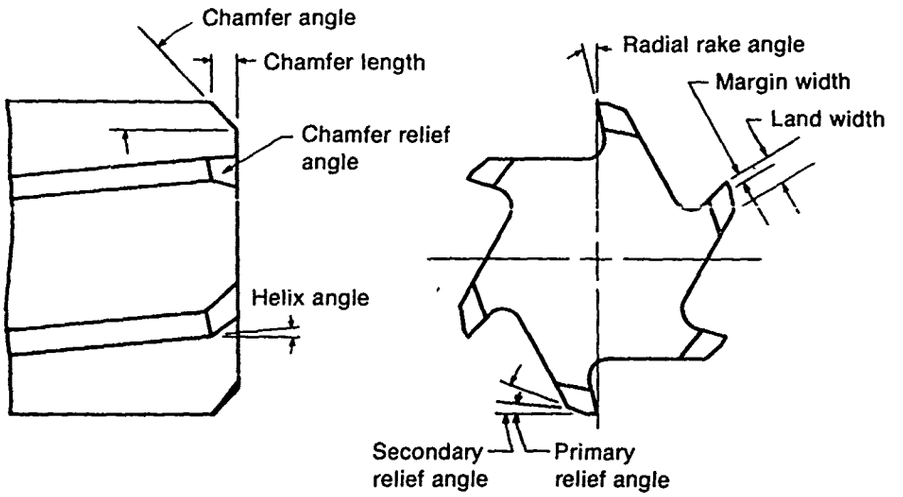
Slash or General Purpose Grind



Stack Grind

(This grind is for difficult to machine alloys and stacked applications)





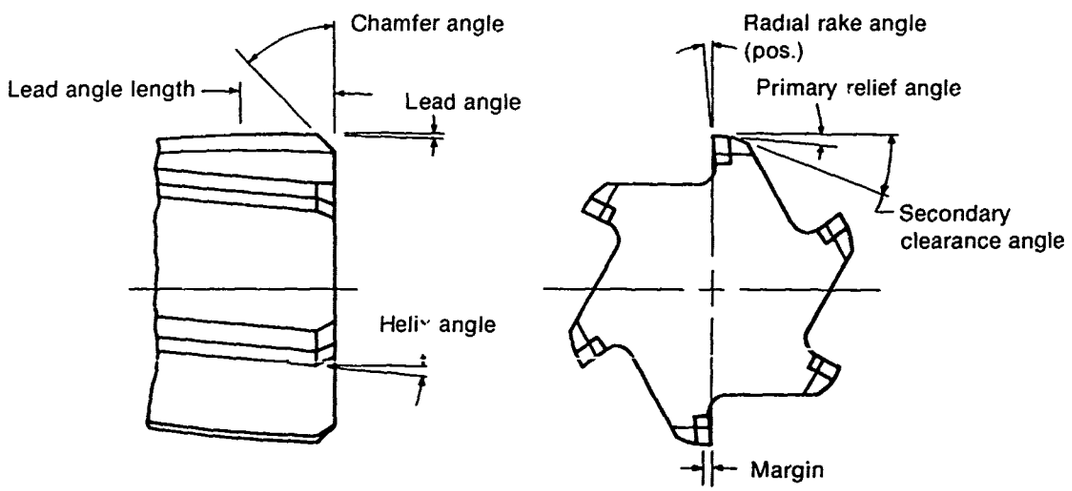
DIAMETER inches	MARGIN WIDTH inch	PRIMARY RADIAL RELIEF ANGLE degrees	CHAMFER ANGLE degrees	CHAMFER RELIEF ANGLE degrees
Under 1/8	0.004-0.006	20 to 25	45	7 to 12
1/8 to 1/4	0.006-0.008	15 to 20	45	7 to 12
1/4 to 1/2	0.008-0.010	11 to 14	45	7 to 12
1/2 to 3/4	0.010-0.015	8 to 12	45	7 to 12
3/4 to 1	0.012-0.017	7 to 10	45	7 to 12
1 to 1-1/2	0.014-0.018	5 to 8	45	7 to 12
1-1/2 to 2	0.016-0.022	5 to 8	45	7 to 12
Over 2	0.018-0.025	5 to 8	45	7 to 12

Reamer Selection Guidelines

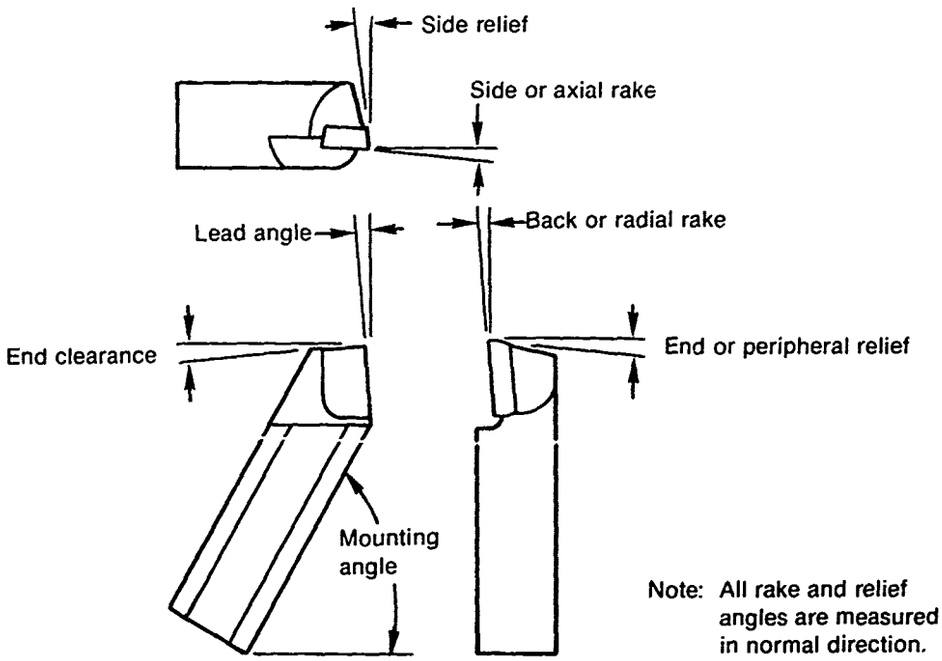
STRAIGHT FLUTE	RIGHT HAND HELIX	LEFT HAND HELIX
• For general purpose use.	• Freer cutting. • Improves finish. • Reduces chatter. • Requires rigid setups with no backlash.	• Reduces chatter on nonrigid setups. • Use 30° to 45° helix for splines and keyways. • Requires more thrust.

15.12 Reamers, Carbide

TOOL GEOMETRY



DIAMETER inches	MARGIN OR CIRCULAR LAND inch	PRIMARY RADIAL RELIEF ANGLE degrees	SECONDARY CLEARANCE ANGLE degrees	LENGTH OF CHAMFER inch	CHAMFER PRIMARY RELIEF ANGLE degrees	CHAMFER SECONDARY CLEARANCE ANGLE degrees
1/4	0.005-0.007	12 to 15	28 to 32	0.020-0.030	10 to 12	25 to 28
3/8	0.005-0.008	12 to 15	28 to 32	0.020-0.030	10 to 12	22 to 24
1/2	0.008-0.010	11 to 13	26 to 28	0.030-0.040	9 to 11	20 to 22
5/8	0.009-0.012	10 to 12	22 to 26	0.040-0.050	8 to 10	18 to 20
3/4	0.010-0.015	9 to 10	20 to 22	0.040-0.050	7 to 9	14 to 18
7/8	0.010-0.015	9 to 10	18 to 20	0.040-0.050	7 to 9	14 to 18
1	0.012-0.015	8 to 10	18 to 20	0.050-0.060	7 to 9	14 to 18
1-1/2	0.014-0.016	7 to 8	16 to 18	0.050-0.060	6 to 8	12 to 16
2	0.018-0.023	7 to 8	16 to 18	0.050-0.060	6 to 8	12 to 16



MATERIAL	HARDNESS Bhn	BACK OR RADIAL RAKE ANGLE* degrees	SIDE OR AXIAL RAKE ANGLE degrees	END OR PERIPHERAL RELIEF ANGLE† degrees	SIDE RELIEF ANGLE degrees
Free Machining Carbon Steels-Wrought	100-425	-3 to -10	0 to 15	5 to 10	2 to 3
Carbon Steels-Wrought and Cast	85-425	-3 to -10	0 to 15	5 to 10	2 to 3
Free Machining Alloy Steels-Wrought	150-425 45R_c-56R_c	-3 to -10	0 to 15	5 to 10	2 to 3
Alloy Steels-Wrought and Cast	125-425 45R_c-56R_c	0 to -6	-3 to -8	5 to 10	2 to 3
High Strength Steels and Maraging Steels-Wrought	175-375 43R_c-56R_c	0 to -6	-3 to -8	5 to 10	2 to 3
Tool Steels-Wrought	100-375 48R_c-56R_c	0 to -6	-3 to -8	5 to 10	2 to 3
Nitriding Steels-Wrought	200-350	0 to -6	-3 to -8	5 to 10	2 to 3
Armor Plate-Wrought	250-320	-5 to -35	15 to 35	5 to 10	2 to 3

NOTE: The lead angle and end clearance are in many cases dictated by part shape and tool holder mounting angles. When a choice is possible, a larger lead angle and a smaller end clearance will usually decrease surface roughness and reduce the tendency to chatter.

*These values are based on boring tool being set on centerline. If tool is set above centerline the radial rake angle should be increased and the end relief angle should be decreased by a value of ϕ = arc tan H/R; where H = height above centerline and R = radius of bored hole.

†These end relief angles apply to bores 1/2 inch and larger. Smaller bores require greater relief angles.

15.13 Boring Tools, Carbide

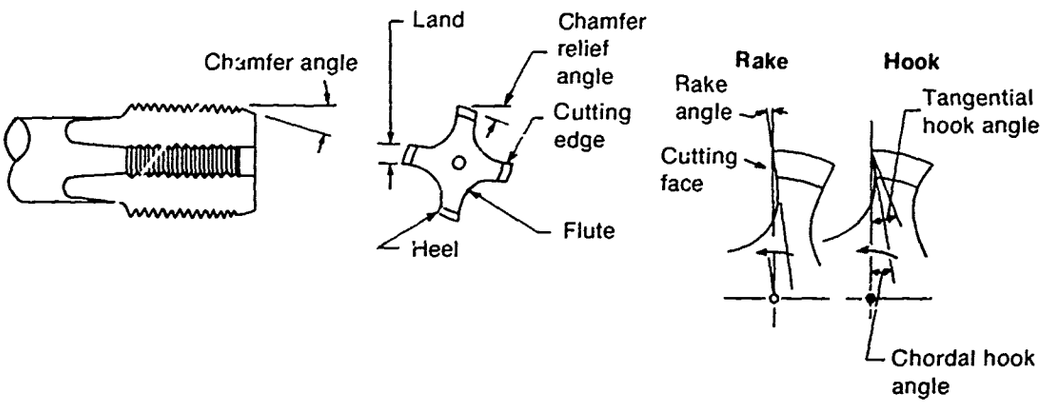
TOOL GEOMETRY

MATERIAL	HARDNESS Bhn	BACK OR RADIAL RAKE ANGLE* degrees	SIDE OR AXIAL RAKE ANGLE degrees	END OR PERIPHERAL RELIEF ANGLE† degrees	SIDE RELIEF ANGLE degrees
Structural Steels-Wrought	100-350	-3 to -10	0 to 15	5 to 10	2 to 3
	350-500	0 to -6	-3 to -8	5 to 10	2 to 3
Free Machining Stainless Steels-Wrought	135-425	3 to 10	0 to 15	5 to 10	2 to 3
Stainless Steels, Ferritic-Wrought and Cast	135-185	3 to 10	0 to 15	5 to 10	2 to 3
Stainless Steels, Austenitic-Wrought and Cast	135-275	3 to 10	0 to 15	5 to 10	2 to 3
Stainless Steels, Martensitic-Wrought and Cast	135-425	3 to 10	0 to 15	5 to 10	2 to 3
Precipitation Hardening Stainless Steels-Wrought and Cast	150-440	3 to 10	0 to 15	5 to 10	2 to 3
Carbon and Alloy Steels-Cast	120-400	0 to -6	-3 to -8	5 to 10	2 to 3
Gray Cast Irons	110-320	0	0	5 to 10	5 to 8
Ductile Cast Irons	140-400	0	0	5 to 10	5 to 8
Malleable Cast Irons	110-280	0	0	5 to 10	5 to 8
Aluminum Alloys-Wrought and Cast	30-150 500 kg	0 to 15	5 to 15	8 to 13	5 to 8
Magnesium Alloys-Wrought and Cast	40-90 500 kg	0 to 15	5 to 15	8 to 13	5 to 8
Titanium Alloys-Wrought	110-440	-3 to -10	-3 to -8	8 to 12	3 to 5
Copper Alloys-Wrought and Cast	40-200 500 kg	0 to 10	5 to 20	8 to 13	5 to 8
Nickel Alloys-Wrought and Cast	80-360	3 to 10	0 to 15	5 to 10	2 to 3
High Temperature Alloys-Wrought and Cast	140-475	3 to 10	0 to 15	5 to 10	2 to 5
Columbium, Molybdenum and Tantalum Alloys-Wrought, Cast, P/M	170-290	0	20	8 to 12	3 to 5
Tungsten Alloys-Wrought, Cast, P/M	180-320	-15	0	5	5
Zinc Alloys-Cast	80-100	0 to 15	5 to 10	8 to 13	5 to 8

NOTE: The lead angle and end clearance are in many cases dictated by part shape and tool holder mounting angle. When a choice is possible, a larger lead angle and a smaller end clearance will usually decrease surface roughness and reduce the tendency to chatter.

*These values are based on boring tool being set on centerline. If tool is set above centerline the radial rake angle should be increased and the end relief angle should be decreased by a value of ϕ = arc tan H/R; where H = height above centerline and R = radius of bored hole.

†These end relief angles apply to bores 1/2 inch and larger. Smaller bores require greater relief angles.



MATERIAL	HARDNESS Bhn	HOOK OR RAKE ANGLE degrees	CHAMFER RELIEF ANGLE degrees	TYPE OF TAP	
				Thru Hole	Blind Hole
Steels-Wrought, Cast & P/M	85-200	7 to 10	8	Spiral Point	Fast Spiral Flute
	200-300	0 to 8	8	Spiral Point	Fast Spiral Flute
	300-375	0	6	Modified 4 Flute Hand Tap	
	375-425	-3 to -6	6	Modified 4 Flute Hand Tap	
	48R_c-52R_c	-5 to -10	4 to 6	Modified 4 Flute Hand Tap*	
Stainless Steels, Ferritic, Martensitic & Precipitation Hardening-Wrought, Cast & P/M	135-275	8 to 12	8	Heavy Duty Spiral Point	Heavy Duty Spiral Flute
	275-325	0 to 5	8	Heavy Duty Spiral Point	Heavy Duty Spiral Flute
	325-425	0	6 to 8	Modified 4 Flute Hand Tap	
Stainless Steels, Austenitic-Wrought, Cast & P/M	135-275	15 to 20	10	Heavy Duty Spiral Point	Heavy Duty Spiral Flute
Gray Cast Irons Ductile Cast Irons Malleable Cast Irons	120-260	5 to 8	6	4 Flute Hand Tap	4 Flute Hand Tap
	260-330	0 to 3	6	Modified 4 Flute Hand Tap	
Aluminum and Magnesium Alloys-Wrought, Cast & P/M	All	10 to 20	12	Spiral Point High Helix	Fast Spiral Flute

*Special taps for these alloys are offered by some tap manufacturers.

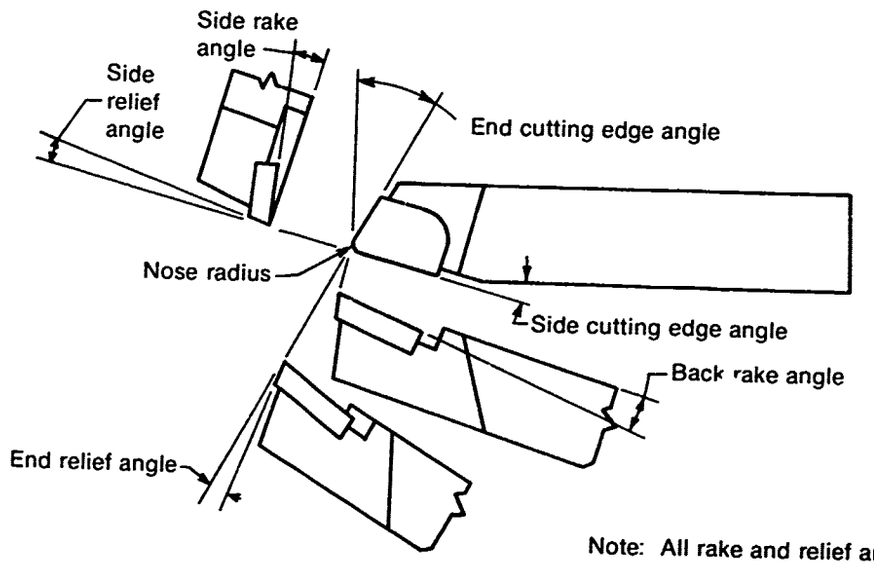
15.14 Taps, High Speed Steel

TOOL GEOMETRY

MATERIAL		HARDNESS Bhn	HOOK OR RAKE ANGLE degrees	CHAMFER RELIEF ANGLE degrees	TYPE OF TAP	
					Thru Hole	Blind Hole
Titanium Alloys- Wrought and Cast		110-275	10 to 15	12	Modified Spiral Point	Modified 4 Flute Hand Tap
		275-440	6 to 10	12	Modified Spiral Point	Modified 4 Flute Hand Tap
Copper Alloys- Wrought, Cast & P/M*	Groups 1 & 2	All	0 to 8	10	Spiral Point	Spiral Flute
	Group 3	All	9 to 18	12	Spiral Point	Fast Spiral Flute
Nickel Alloys, Magnetic Alloys, Controlled Expansion Alloys- Wrought, Cast & P/M		80-170	9 to 12	6 to 8	Spiral Point	Spiral Flute
High Temperature Alloys -Wrought and Cast		140-425	0 to 10	4 to 6	2 Flute Spiral Point*	3 Flute Hand Tap* Interrupted Thread
Columbium, Molybdenum & Tantalum Alloys-Wrought, Cast & P/M		170-290	10 to 12	6 to 8	2 Flute Spiral Point*	4 Flute Hand Tap*
Magnetic Core Iron		185-240	12 to 15	6 to 8	2 Flute Spiral Point	Spiral Flute
Zinc Alloys-Die Cast		80-100	12 to 15	12	Spiral Point High Hook	Fast Spiral Flute
Thermoplastics		All	5 to 8	12	Spiral Point High Hook	Fast Spiral Flute
Thermoset Plastics		All	0 to 3	12	Modified 4 Flute Hand Tap	

*See section 15.2 for copper alloy groups.

*Special taps for these alloys are offered by some tap manufacturers.



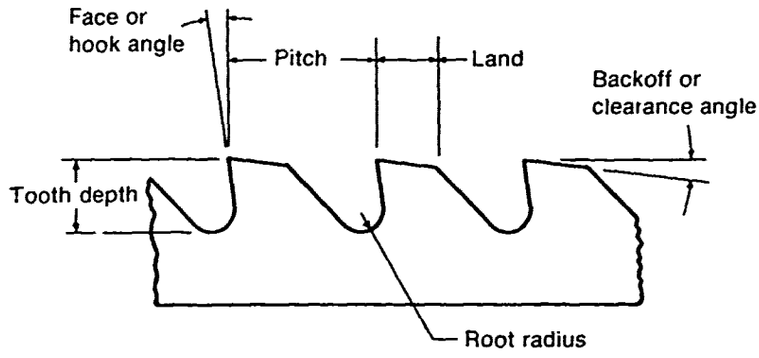
Note: All rake and relief angles are measured in normal direction.

15.15 Planing Tools

TOOL GEOMETRY

MATERIAL	HARDNESS Bhn	HIGH SPEED STEEL					CARBIDE				
		Back Rake Angle degrees	Side Rake Angle degrees	End Relief Angle degrees	Side Relief Angle degrees	End Cutting Edge Angle degrees	Back Rake Angle degrees	Side Rake Angle degrees	End Relief Angle degrees	Side Relief Angle degrees	End Cutting Edge Angle degrees
Free Machining Carbon Steels-Wrought **Carbon Steels-Wrought and Cast** **Free Machining Alloy Steels-Wrought** **Alloy Steels-Wrought and Cast** **High Strength Steels-Wrought** **Maraging Steels-Wrought** **Tool Steels-Wrought** **Nitriding Steels-Wrought** **Armor Plate-Wrought** **Structural Steels-Wrought**	85 to 375	5 to 10	6 to 10	10 to 15	6 to 10	5 to 15	0 to -5	15 to -15	3 to 5	3 to 5	4 to 15
Free Machining Stainless Steels-Wrought **Stainless Steels, Ferritic-Wrought and Cast** **Stainless Steels, Austenitic-Wrought and Cast** **Stainless Steels, Martensitic-Wrought and Cast** **Precipitation Hardening Stainless Steels-Wrought and Cast**	135 to 325	5 to 10	6 to 10	10 to 15	6 to 10	5 to 15	0 to -5	5 to -15	4 to 6	4 to 6	4 to 15
Gray Cast Irons **Ductile Cast Irons** **Malleable Cast Irons**	100 to 330	3 to 8	5 to 10	2 to 5	2 to 5	8 to 15	8 to -5	15 to -3	4 to 6	4 to 6	8 to 10
Aluminum Alloys-Wrought and Cast	30 to 150 500 kg	10 to 20	30 to 40	8 to 15	8 to 15	7 to 9	–	–	–	–	–
Magnesium Alloys-Wrought and Cast	40 to 90 500 kg	10 to 20	30 to 40	8 to 15	8 to 15	7 to 9	–	–	–	–	–
Copper Alloys-Wrought and Cast	40 to 200 500 kg	5 to 10	5 to 10	8 to 12	8 to 12	5 to 15	–	–	–	–	–
Nickel Alloys-Wrought and Cast	80 to 320	0 to 5	5 to 10	4 to 10	4 to 10	10 to 15	–	–	–	–	–

NOTE: For all materials and for both high speed steel tools and carbide tools, use a 0°–30° side cutting edge angle. For best chip flow when planing mild and medium hard steels, try a 23° side cutting edge angle.



MATERIAL		HARDNESS Bhn	HOOK ANGLE degrees	CLEARANCE ANGLE degrees
Free Machining Carbon Steels-Wrought Alloy Steels-Wrought and Cast		100-375	15 to 20	2 to 3
Carbon Steels-Wrought		85-375	15 to 20	1 to 2
Carbon Steels-Cast Alloy Steels-Wrought and Cast High Strength Steels-Wrought Maraging Steels-Wrought		120-375	8 to 15	1 to 3
Tool Steels-Wrought Armor Plate-Wrought		100-375	8 to 12	1 to 2
Nitriding Steels-Wrought		200-350	8 to 15	1 to 2
Free Machining Stainless Steels-Wrought Stainless Steels, Martensitic-Wrought and Cast		135-425	8 to 12	1 to 2
Stainless Steels, Ferritic-Wrought and Cast		135-185	12 to 18	2 to 3
Stainless Steels, Austenitic-Wrought and Cast		135-275	12 to 18	1/2 to 2
Precipitation Hardening Stainless Steels-Wrought and Cast		150-440	10 to 15	2
Gray Cast Irons		110-320	6 to 8	2 to 3
Ductile and Malleable Cast Iror		110-400	8 to 15	2 to 3
Aluminum Alloys-Wrought and Cast		30-150 500 kg	10 to 15	1 to 3
Magnesium Alloys-Wrought and Cast		40-90 500 kg	10 to 15	1 to 3
Titanium Alloys-Wrought		110-440	8 to 20	2 to 8
Copper Alloys-Wrought and Cast*	Group 1	40-200 500 kg	-5 to 5	1 to 2
	Group 2	40-200 500 kg	0 to 10	1 to 2
	Group 3	40-200 500 kg	10 to 15	2 to 3
Nickel Alloys-Wrought and Cast		80 to 360	12 to 18	1/2 to 2
High Temperature Alloys-Wrought and Cast		140-475	15 to 20	2 to 8
Zinc Alloys-Cast		80-100	10 to 15	2 to 5

*See section 15.2 for copper alloy groups.

15.17 Tool and Cutter Angles—Approximate Equivalents

TOOL GEOMETRY

LATHE AND PLANER	MILLING CUTTER	DRILL	BROACH
Back Rake Angle	Axial Rake Angle	Helix Angle	Hook Angle
Side Rake Angle	Radial Rake Angle	Radial Rake Angle	Side Rake Angle
Side Cutting Edge Angle	Corner Angle	1/2 Point Angle	–
End Cutting Edge Angle	End Cutting Edge Concavity Angle	–	–
Side Relief Angle	Radial Relief Angle	–	Clearance Angle
End Relief Angle	Axial Relief Angle	Lip Relief Angle	Clearance Angle

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Cutting Fluid Selection and Use 16.1

INTRODUCTION

When properly applied, cutting fluids can increase productivity and reduce costs by making possible the use of higher cutting speeds, higher feed rates and greater depths of cut. Effective application of cutting fluids can also lengthen tool life, decrease surface roughness, increase dimensional accuracy and decrease the amount of power that is consumed when cutting dry. Knowledge of cutting fluid functions, types, physical limitations and compositions plays an important role in the selection and application of the proper fluid for a specific machining situation. Cutting fluid recommendations for various machining operations and work materials are given in section 16.2.

FUNCTIONS OF CUTTING FLUIDS

Depending upon the machining operation being performed, a cutting fluid has one or more of the following functions:

- Cooling the tool, workpiece, and chip
- Lubricating (reducing friction and minimizing erosion on the tool)
- Controlling built-up edge (BUE) on the tool
- Flushing away chips
- Protecting the workpiece from corrosion

The relative importance of each function depends upon the work material, the cutting tool, the cutting conditions and the finish required on the part.

TYPES OF CUTTING AND GRINDING FLUIDS

Many cutting fluids are available today to satisfy the requirements of modern machine tools. High speed cutting and grinding, increased metal removal rates, the emergence of new tool and work materials, and the demands for smoother finishes and closer tolerances have all contributed to the continual development of a wider variety of fluids that satisfy more specific requirements.

Although there is no all-purpose cutting fluid, some fluids offer considerable versatility while others are tailored for spefific applications. For economic reasons, most metalworking firms try to use as few different fluids as possible. Preferred fluids have long life and do not require constant changing or modifying.

Each of the basic types of fluids has distinctive features, advantages and limitations, although the dividing line is not always clearly identifiable. Understanding these basic differences is necessary to obtain optimum performance.

The four basic types of cutting fluids are as follows:

Cutting oils

- straight and compounded mineral oil (plus additives)

Water-miscible (water-soluble) fluids

- emulsifiable oils (soluble oils)
- chemical (synthetic) fluids
- semichemical (semisynthetic) fluids

Gases

Paste and solid lubricants

The cutting oils and the water-miscible fluids are the types most commonly used. Each of these has distinctive advantages over the other, depending on the type of machining operation and the material being machined. Cooling is best accomplished by water-miscible fluids, while oil-base fluids provide better lubrication.

Cutting Oils

Cutting oils have a mineral oil base and may be used straight (uncompounded) or compounded (combined with polar additives and/or chemically active or inactive additives or compounds). They have excellent lubrication properties, good rust control and long life, but they do not cool as well as water-miscible fluids. Oils may be classified as inactive or active.

Inactive Cutting Oils

Inactive cutting oils (compounded with chemically inactive additives), have relatively high lubricity but low or no anti-welding properties. They have nonstaining properties which prevent discoloration of chemically sensitive materials.

Straight mineral oils do not have as good lubrication properties as do the compounded types, but they are lower in cost. Straight mineral oils are generally restricted to light-duty operations on metals that are easier to machine, such as aluminum, magnesium, brass and sulfurized or leaded free-machining steels, where the lubrication and cooling requirements are not severe. The oils are noncorrosive and stable and, if kept clean, can be used almost indefinitely. They lubricate all exposed moving parts, and minor leakage into or from gear boxes, bearings and hydraulic systems does not upset a machine's performance.

Fatty oils were once widely used as cutting fluids. The most common types are lard and rape seed oil. Their use has declined, partly because they are now difficult to obtain and are expensive, but mainly because modern additives blended with mineral oil are much more effective. Fatty oils are very polar and have high "oiliness"—anti-friction performance—but poor anti-weld characteristics. They oxidize readily and display a tendency to fume and to emit unpleasant odors.

Compounded cutting oils are made by blending polar additives and/or chemically active additives with mineral oil. Polar additives, such as certain fats, oils, waxes and synthetic materials, increase the load-carrying and cutting capability of mineral oil. Common polar additives are lard oil and castor oil. The function of any polar additive is to wet and to penetrate the chip/tool interface by reducing the interfacial tension between the carrier mineral oil and the

metal. Such additives have been refined to minimize previous objections to the formation of disagreeable odors and the tendency to gum.

Fatty-mineral oils are combinations of one or more fatty oils blended in straight mineral oil. Lard oil is frequently used for this purpose Fatty oils may comprise up to 40 percent of the blend depending on the application and are quite effective for many operations. The advantages are not great and are confined primarily to improvement of finish in the machining of mild steel, brass, copper and aluminum Such blends are particularly suitable for machining the harder types of brass and copper, where straight mineral oil may not give the finish required and where the use of more active oils would cause staining. These oils are widely used in automatic screw machines where the operations are not exceptionally severe.

Extreme pressure (EP) additives are added to fluids used for machining operations where cutting forces are particularly high, such as tapping and broaching, or for operations performed with heavy feeds. Chemical or EP additives provide a tougher, more stable form of lubrication at the chip-tool interface. These additives include sulfur, chlorine or phosphorus compounds that react at high temperatures in the cutting zones to form metallic sulfides, chlorides and phosphides In addition to providing extreme pressure lubrication, these additives provide a film on the tool surface with anti-weld properties that minimize the built-up edge. Sulfurized fatty-mineral oil blends have sulfur added in a strongly bonded, inactive form which may be totally nonstaining.

Active Cutting Oils

Active cutting oils (compounded with chemically active additives) include sulfurized or phosphorized mineral oils, sulfo-chlorinated mineral oils, and sulfo-chlorinated fatty-mineral oil blends. These fluids have good anti-weld and extreme pressure lubrication qualities which improve tool life in high-temperature and high-pressure applications. They may, however, cause discoloration or staining of certain metals.

Sulfur can be added to a cutting oil in the form of sulfurized mineral oil or sulfurized fat. The sulfurized mineral oil is more active at lower temperatures and tends to severely stain aluminum, copper, brass, bronze and magnesium alloys. In comparison, the sulfurized fatty oil (which is sulfurized at a higher temperature) will not release sulfur as readily and. therefore, has less tendency to stain nonferrous metals or steel. Oils containing sulfur will form metallic sulfide films which will act as solid lubricants at temperatures up to about 1300°F [700°C].

Chlorine reacts and functions in essentially the same manner as sulfur. Inhibiting ingredients are added to prevent corrosion of ferrous surfaces, since chlorine is more reactive than sulfur. Chemical reaction is thus restricted to the chip-tool interface, where the temperatures are high. Chlorinated oils form an iron chloride film when reacting with ferrous workpiece materials or high speed steel tools. This film has a low shear strength and provides low friction up to about 750°F [400°C], beyond which it decomposes. Chlorinated oils usually will not stain nonferrous alloys.

When both chlorine and sulfur are added to cutting oils, anti-weld or EP characteristics are effective over a wider temperature range. Sulfo-chlorinated mineral oil and sulfo-chlorinated fatty oils are examples of such oils which are suitable for a wide range of applications.

Phosphorus performs as a mild EP lubricant or anti-friction additive when added to a cutting oil. The phosphide film breaks down at lower temperatures than do sulfide or chloride films and, therefore, is not as effective an anti-weld agent. Phosphorus is most effective in reducing friction and wear. These oils are nonstaining to most ferrous and nonferrous alloys.

These basic types of cutting oils can have various additive levels and may be used singly or in combination and at various viscosities to suit various applications. Some recent developments include oils in which the production of fume and oil-mist have been significantly reduced.

Applications of all compounded cutting oils (both active and inactive) are generally limited to machining operations on difficult-to-machine metals or form grinding from the solid. The high cost, the possible danger from smoke and fire, and the operator health problems often restrict the use of these oils to operations where other fluids do not provide satisfactory performance.

Water-Miscible (Water-Soluble) Fluids

The water-miscible (water-soluble) cutting fluids are primarily used for high speed machining operations because they have better cooling capabilities. These fluids are also best for cooling machined parts to minimize thermal distortion.

Water-miscible cutting fluids are mixed with water at different ratios depending on the machining operation. For high-speed chip-making operations, they are normally mixed 1 part concentrate to 20 to 30 parts water. For many grinding operations where it is desirable to have a lighter fluid with more cooling action, the ratio is 1:40 or 1:50. Water-miscible fluids form mixtures ranging from emulsions to solutions when mixed with water. Because water has a high specific heat, high thermal conductivity and high heat of vaporization, it is one of the most effective cooling media known. Blended with water, the water-miscible fluids provide the combined cooling and moderate lubrication required by metal removal operations conducted at high speeds and lower pressures.

The water-miscible fluids can be classified as emulsifiable oils (soluble oils), chemical (synthetic) fluids or semi-chemical (semisynthetic) fluids. Fluids within these classes are available for light-, medium-, and heavy-duty performance.

Emulsifiable Oils

Emulsifiable oils are commonly called soluble oils, emulsions, or emulsifiable cutting fluids. An emulsion is a suspension of oil droplets in water made by blending the oil with emulsifying agents and other materials. These emulsifiers (soap or soap-like materials) break the oil into minute

particles and keep the particles dispersed in water for long periods of time. Bactericides—usually nonphenolic organic compounds specifically approved by the Environmental Protection Agency (EPA)—are added to control the growth of microorganisms such as bacteria, algae and fungi. If disposal is of no concern, phenolics may be used. The soaps, wetting agents, and couplers used as emulsifiers in water-miscible fluids reduce surface tension signficantly. As a result, the liquid has a greater tendency to foam when subjected to shear and turbulence. For this reason, water-miscible fluids sometimes cause foaming problems in operations such as gundrilling or flat-bed and double-disk grinding. With the use of special wetting agents and foam depressants, however, water-miscible fluids can be rendered sufficiently nonfoaming to be effective in almost all operations.

Emulsifiable oils combine the lubricating and rust-prevention properties of oil with water's excellent cooling properties. Emulsions, with their cooling-lubricating properties, are most effectively used for metalcutting operations with high cutting speeds and low cutting pressures accompanied by considerable heat generation.

Advantages of emulsifiable oils over straight or compounded cutting oils include greater reduction of heat, cleaner working conditions, economy resulting from dilution with water, better operator acceptance and improved health and safety benefits. They can be used for practically all light- and moderate-duty cutting operations, as well as for most heavy-duty applications except those involving extremely difficult-to-machine materials. Emulsifiable oils can be used for practically all grinding operations with the exception of severe grinding operations, such as form, thread and plunge grinding where wheel form is a critical factor. Extreme-pressure, compounded emulsifiable oils do not suffer from this limitation.

Cutting fluid manufacturers supply emulsifiable oils as concentrates that the user prepares by mixing with water. Mixtures range from 1 part oil in 100 parts water to a 1:5 oil-water ratio. The leaner emulsions are used for grinding or light-duty machining operations where cooling is the essential requirement. Lubricating properties and rust prevention increase with higher concentrations of oil. The four types of emulsifiable oils are summarized in table 16.1-1.

General-purpose soluble oils are milky fluids with mineral oil droplets of 0.0002-inch to 0.008-inch [0.005 mm to 0.2 mm] diameter. They are commonly used at dilutions of 1:10 to 1:40 for general purpose machining.

Clear-type (or translucent) soluble oils contain less oil (with higher proportions of corrosion inhibitors) and considerably more emulsifier than do milky emulsions. The clear type, therefore, consists of oil dispersions with smaller oil droplets which are more widely distributed. Since there is less dispersion of transmitted light, the fluid is less opaque, and the result is a translucent liquid. The translucency is not permanent, though, because often times the tiny oil droplets tend to coalesce and form larger droplets. These oils are generally used for grinding or for light-duty machining.

Fatty soluble oils have animal or vegetable fats or oils or other esters added to the mineral oil content to provide a range of fluids with enhanced lubricating properties.

EP soluble oils contain sulfur, chlorine or phosphorus additives to improve load-carrying performance Since the EP concentrate is diluted 5 to 20 times when the emulsion is prepared, the lubricating capability is reduced. Where the lubricating capabilities of soluble-oil emulsions and the cooling properties of cutting oils are inadequate, EP soluble oils can satisfy both requirements in many cases. These fluids, commonly known as heavy-duty soluble oils, have in some cases replaced cutting oils for broaching, gear hobbing, gear shaping, and gear shaving.

Chemical Fluids

Chemical (synthetic) fluids are chemical solutions consisting of inorganic and/or other materials dissolved in water and containing no mineral oil. All of these fluids are coolants; some are also lubricants. Chemical agents that go into these fluids include: amines and nitrites[1] for corrosion inhibitors; nitrates, for nitrite stabilization; phosphates and borates, for water softening; soaps and wetting agents, for lubrication and reduction of surface tension; phosphorus, chlorine and sulfur compounds, for chemical lubrication; glycols, as blending agents and humectants; and germicides, to control the growth of bacteria.

In general, the advantages of chemical fluids include economy, rapid heat dissipation, good size control, detergent properties which help keep the machine surfaces and the coolant systems clean, excellent workpiece visibility, easy mixing with little agitation, and high resistance to rancidity and rust. The increased cost of oils, plus OSHA and EPA requirements, may result in increased use of these and other water-miscible fluids.

A possible disadvantage of chemical fluids that may be encountered in some severe operations is insufficient lubricity, which may cause sticking and/or wear of moving machine tool parts. The dry, powdery residue or film left by chemical fluids is easy to remove. This residue can interfere with component movements if allowed to remain on the machine surfaces. Most of the stickiness is caused by the minerals in the water used. The mineral content in water can quadruple in six weeks as water is added to replace that lost by evaporation. Deionized water should be used to avoid this problem. Improved lubricating or EP properties, however, can be provided. Other limitations may include foaming problems in high agitation applications, and high detergency and alkalinity characteristics which may irritate sensitive hands when the concentration of the mix is not controlled.

Chemical fluids are usually classified into two general groups: true solutions and surface-active types (see table 16.1-1).

[1]CAUTION: The use of fluids containing nitrites may present a hazard and is presently under review by the National Institute of Occupational Safety and Health (NIOSH). Nitrites can react with amines to form nitrosamines which are carcinogenic. NIOSH may ban or control the use of nitrites in cutting fluids after completion of their review.

16.1 Cutting Fluid Selection and Use

TABLE 16.1–1 Water-Miscible Cutting Fluids

CLASS	TYPE	GENERAL CHARACTERISTICS
Emulsifiable Oils	(1) General-Purpose Soluble Oils	Used at dilutions between 1:10 and 1.40 to give a milky emulsion. Used for general purpose machining
	(2) Clear-Type Soluble Oils	Used at dilutions between 1:50 and 1:100. Their high emulsifier content results in emulsions which vary from translucent to clear. Used for grinding or light-duty machining.
	(3) Fatty Soluble Oils	Used at similar concentrations to (1) and of similar appearance. Their fat content makes them particularly good for general machining operations on nonferrous metals
	(4) EP Soluble Oils	Generally contain sulfurized or chlorinated EP additives. Used at dilutions between 1:5 and 1:20 where a higher performance than that given by (1), (2) or (3) is required.
Chemical (Synthetic) Fluids	(1) True Solutions	Essentially solutions of chemical rust inhibitors in water Used at dilutions between 1:50 and 1:100 for grinding operations on iron and steel.
	(2) Surface-Active Chemical Fluids	Contain mainly water-soluble rust inhibitors and surface-active load-carrying additives Used at dilutions between 1:10 and 1:40 for cutting and at higher dilutions for grinding. Most are suitable for both ferrous and nonferrous metals.
	(3) EP Surface-Active Chemical Fluids	Similar in characteristics to (2) but containing EP additives to give higher machining performance when used with ferrous metals. Used at dilutions between 1:5 and 1:30.
Semichemical (Semisynthetic) Fluids	—	Essentially a combination of a chemical fluid and a small amount of emulsifiable oil in water forming a translucent, stable emulsion of small droplet size. EP additives are usually included permitting their use for moderate- and heavy-duty machining and grinding applications.

True-solution fluids (without wetting agents), also called chemical solutions or chemical grinding fluids, primarily contain rust inhibitors (inorganic and organic nitrites[2]), sequestering agents, amines, phosphates, borates, glycols or ethylene or propylene oxide condensates. Some of these fluids contain highly developed corrosion inhibitors such as sodium nitrite[2] (for cast iron), triethanolamine (for both cast iron and steel) and sodium mercaptobenzothiazole (for reducing corrosion on brass, zinc and aluminum). True solutions, used at 1:50 or 1:100 ratios, are clear in appearance but are often colored with dyes to indicate their presence in water. These fluids are restricted to grinding operations where they prevent rust and permit rapid heat removal. True solutions have high surface tension (about equivalent to water). They have a tendency to leave a residue of hard or crystalline deposits formed by water evaporating. These chemicals can also be added to emulsifiable oils or to other chemical fluids to enhance their corrosion-inhibiting properties.

[2]CAUTION. The use of fluids containing nitrites may present a hazard and is presently under review by the National Institute of Occupational Safety and Health (NIOSH). Nitrites can react with amines to form nitrosamines which are carcinogenic. NIOSH may ban or control the use of nitrites in cutting fluids after completion of their review

Surface-active chemical fluids are extremely fine colloidal solutions composed of inorganic and organic materials dissolved in water with the addition of wetting agents (surface active agents). The wetting agents improve the wetting action of the water and provide greater uniformity of both heat dissipation and anti-rust action. This type of fluid may include anti-foaming agents, humectants, mild lubricants (organic or inorganic) and water softeners. The lubricating (anti-wear) properties may be provided by a viscous polyglycol compound. Corrosion protection may be provided by a mixture of triethanolamine and caprylic acid, and the formulation may include a deactivator for copper alloys.

The surface-active type of chemical fluid has fair lubricity, low surface tension, and good rust-inhibiting properties and usually leaves a dry, hard or powdery residue that is easily removed. The slight tendency of these fluids to foam is usually not a serious problem in most operations. They are usually used at dilutions of 1 part concentrate in 10 to 40 parts water.

EP surface-active chemical fluids are similar to the plain (general-purpose) surface-active type but have chlorine, sulfur or phosphorus additives to provide extreme-pressure lubrication effects. These fluids are diluted at one part concentrate to between 5 and 30 parts water for tougher machining operations.

Semichemical Fluids

Semichemical fluids or semisynthetic fluids are essentially a combination of chemical fluids and emulsifiable oils in water. These fluids are actually preformed chemical emulsions that contain only a small amount of emulsified mineral oil, about 5 to 30 percent of the base fluid, which has been added to form a translucent, stable emulsion of small droplet size. Since the usual EP additives can be incorporated (often more readily in the oil content than in the synthetic base), the lubricating performance can be varied to permit using such fluids for moderate- and heavy-duty machining and grinding applications

Semichemical fluids combine some of the best qualities of chemical fluids and emulsifiable oils. The advantages and limitations are similar to those described for chemical fluids, except that semichemical fluids have better lubricating properties than do chemical fluids. They are also cleaner, with better rust and rancidity control than emulsifiable oils.

Gases

Air is the most common gaseous fluid. It is present under atmospheric pressure for dry operations and also present when fluids are used. Air is sometimes compressed to provide better cooling, with a stream directed at the cutting zone to remove heat by forced convection. This also can be used to blow chips away, but safety precautions must be observed. Gases such as argon, helium and nitrogen are sometimes used to prevent oxidation of the workpiece and the chips, but the high cost of these gases generally makes them uneconomical for production applications.

Gases, such as Freon™ or CO_2, with boiling points below room temperature can be compressed and sprayed into the cutting zone to provide evaporative cooling. Use of liquid argon or nitrogen allows cooling to several hundred degrees below zero. Care is necessary, however, to prevent part warpage caused by large temperature differentials.

Advantages of inert gases include good cooling ability, increased tool life, a clear view of the operation, elimination of mist, and no contamination of the workpiece, chips or machine lubricants. The cost of some of these gases, however, can be extremely high.

Paste and Solid Lubricants

There are also paste and solid lubricants that are usually applied manually by brush or by oilcan to the tool or workpiece in operations such as tapping and hand reaming. Grinding wheels are sometimes impregnated with solids possessing lubricating qualities. In special cases, such as knife grinding, wheels are treated with sulfur to produce a cooler action in wet grinding. Also, external application of grease sticks to grinding wheels can provide some lubrication, but this requires performing the operation dry. Solid waxes in stick form can be used on grinding wheels, sanding disks or belts, taps, and end- or circular-saw blades for lubrication to improve finish and tool life or to reduce burring or metal welding. Other solids most often used as heavy-duty lubricants include graphite, molybdenum disulfide, pastes, soaps and waxes.

SELECTION OF A CUTTING FLUID

The proper choice of a cutting fluid depends on many complex interrelated factors. Of primary concern are machinability (or grindability) of the material, compatibility (metallurgical, chemical and human) and acceptability (fluid properties, reliability and stability).

Machinability

The selection of the type of cutting fluid for use should be based on:

- Type of machining operation
- Material being machined
- Tool material
- Machining conditions—cutting speed, feed, and depth of cut

One of the most important factors in selecting a cutting fluid is the nature of the cutting operation itself. The various machining processes naturally differ in metal removal characteristics. The more difficult operations will place greater demands on a cutting fluid. Selection is, therefore, a matter of assessing the severity of the machining operation and marrying it to the appropriate cutting fluid. The approximate ratings for the machining processes in order of decreasing severity, are as follows:

1. Internal broaching
2. External broaching
3. Tapping
4. Threading
5. Generation of gear teeth
6 Deep drilling
7. Boring
8. Screw machining with form tools
9. High-speed, light-feed screw machining
10. Milling
11. Drilling
12. Planing and shaping
13. Turning, single-point tools
14. Sawing
15. Grinding

These ratings cannot be regarded as absolute, since variations in the tool geometry and workpiece material will change the severity of the machining operation.

For heavy-duty machining operations (such as tapping or broaching), medium- or heavy-duty cutting oils are generally used. Horizontal broaching of steel usually requires a heavier-bodied or more-chemically-active oil than does vertical surface broaching under comparable conditions. The heavier oil clings to the horizontal broach better than a water-miscible fluid, and chemical activity aids in efficient cutting. For vertical surface broaching of mild steels, emulsions or solutions may be used, but the usual choice is an oil.

Cutting oils can be ranked in order of increasing load-carrying capacity as follows:

1. Straight mineral oil
2. Mineral oil with fatty additives

3. Mineral oil with chlorinated additives
4. Mineral oil with sulfurized fatty additives
5. Mineral oil with free sulfur and sulfurized or chlorinated compounds

Slow speed operations require the lubricating properties of cutting oils As a general rule, cutting oils should be used at cutting speeds below 100 feet per minute [30 m/min]. Cutting oils with EP lubricants are effective in a wide variety of machining operations on many materials up to speeds of 200 feet per minute [60 m/min]. At speeds of about 200 feet per minute [60 m/min], chemical action is much less effective than at the lower speeds. Chemical action diminishes quickly and becomes virtually nil as the cutting speed is increased to 400 feet per minute [120 m/min].

Both tapping and threading involve many small cutting edges in continuous contact with the work throughout the cut. The design of the tools and the nature of these operations shield the edges of the tools from the flow and the cooling effect of the cutting fluid, particularly in tapping

Drilling can be a difficult operation when done on difficult-to-machine materials. Drilling speeds are generally slower than those used for other operations because the cutting edge is in continuous contact with the metal when cutting and the cutting edges are shielded from the flow and beneficial cooling action of the cutting fluid. The preferred fluids for conventional drilling operations are emulsifiable oils and sulfurized or chlorinated mineral oils. These fluids provide some lubricity to prevent chatter and friction-generated heat while carrying away the heat generated by chip formation. Oil-hole drills should be used wherever possible.

There are some operations for which oils are specially formulated. For example, honing requires the use of a thinner, paraffinic-base oil.

For many high speed operations, such as grinding and turning or milling with carbides, the most important benefit is provided by the superior cooling characteristics of the water-miscible fluids. In such instances, lubrication and anti-weld properties are less important. At high speeds, time for reaction between fluid additives and the workpiece is reduced to a minimum. Further, the higher relative velocities of the work and the tool virtually preclude the fluid's reaching the work zone. Consequently, gross cooling is required to prevent catastrophic tool failure from crater wear, to prevent distortion in the workpiece from heat buildup and to control workpiece size.

Some emulsifiable oils and chemical fluids are formulated specifically for grinding operations and are used in concentrations of 1 part concentrate in 25 to 60 parts water. An increase in the richness of emulsifiable oil mixtures from 2.5 percent to 10 percent can improve the grinding ratio and the workpiece finish and reduce horsepower requirements. Note that the grinding ratio is a measure of the volume of material removed per unit volume of wheel wear.

Severe grinding operations, such as form, thread, and plunge grinding where wheel form is a critical factor, require the use of cutting oils or EP-compounded emulsifiable oils. It should be noted that for the low stress grinding technique, the use of an oil-base fluid results in less surface distortion. Grinding oils reduce friction, thus reducing the heat generated. They permit heavier cuts to be taken, produce smoother finishes, reduce wheel breakdown, and, hence, allow better form control. Oils suffer from the disadvantages of allowing heat buildup in the workpiece, tending to hold chips in suspension, and smoking or burning. The messiness of oil vapors is also a nuisance.

In summary, from a machinability viewpoint, cutting and grinding fluids should be selected to provide the following:

Greater Lubrication

- at relatively low speeds
- on the more difficult-to-machine materials
- for more difficult operations
- for better surface finish

Greater Cooling

- at relatively high speeds
- on the easier-to-machine materials
- for easier operations
- where heat buildup in the part is a problem

Types of cutting fluids recommended for various work materials and machining operations are listed in section 16.2.

Other Considerations

A number of other important factors must be considered when selecting cutting and grinding fluids. These include compatibility of the fluid with the material being machined, the quality of the water in which it is mixed, tramp oil contamination and the machine tool. The acceptability of the fluid, in terms of its properties, reliability and stability, is also important. Other factors to be considered include the quantity of fluid used and the method of application, facilities for storing, handling, cleaning or recycling the fluid, the quality of water used in the aqueous emulsions or solutions, and the rust and rancidity control necessary. Economic considerations include any waste treatment facilities that may be required prior to disposal. The cutting fluid's effect on the total machining cost per piece must be considered, since the more expensive fluids may sometimes be more economical in the long run.

Compatibility with Workpiece Material

The cutting fluid selected for use must be compatible with the material being machined. The fluid should not cause staining or corrosion of the workpiece. It should prevent corrosion of the workpiece during machining, while as work-in-progress waiting for transfer, and possibly while in storage for a reasonable time. Care should be taken when selecting coolants from a corrosion standpoint, especially for nonferrous work materials.

Some copper alloys cannot be machined with highly sulfurized cutting oils since the active sulfur will stain the machined surface. Sulphur is often used in a form in which it

is chemically combined with fatty oils, although for severe machining operations it is often used at low concentrations in its natural form as free sulfur. In this latter or active form, however, it is very reactive toward copper. For this reason, cutting fluids containing free sulfur should never be used in the machining of copper or its alloys.

Metals such as aluminum, magnesium and zinc (also galvanized steel) are attacked by acids or alkalies, thus causing corrosion. Selection of a cutting fluid for aluminum depends on the alloy. Active sulfur or chlorine additives may cause staining of some aluminum alloys. There are some fluids, however, with patented additives that improve finishes and help prevent staining. The use of highly alkaline grinding fluids on aluminum would probably produce badly corroded parts. Magnesium and its alloys, for example, *should never* be machined or ground with water-miscible fluids because the metal has an incendiary effect in water. Zinc and galvanized steel should not be machined with nitrite-containing fluids; oil-rich emulsions with a pH of approximately 8.0 have been found effective for machining these metals. Special fluids available for machining copper, aluminum and magnesium are listed in section 16.3.

Ferrous metals dissolve when attacked by acids and rust will form. Alkalies form a protective layer on most ferrous metals to prevent corrosion. Cutting fluids for ferrous metals are therefore kept on the alkaline side—to inhibit rusting of machines and machined parts.

Fluid concentration should be maintained; otherwise, the rust-inhibiting properties will be reduced. Some rust inhibitors are attacked by oxygen and acids in the air and in the water; eventually, the inhibitors will be used up.

The rust-inhibiting effect of soluble oils is rapidly lost when machining cast iron. Therefore, it is advisable to add some soluble oil concentrate regularly in order to maintain the proper concentration. To prevent corrosion, soluble oils must be 2 to 3 times more concentrated when machining cast iron than when machining steel.

Particular care should be exercised in selecting cutting fluids used for machining components which are highly stressed in service and which are exposed to unusual environments. For such parts, cutting fluids should be used which will not make the part vulnerable to stress corrosion attack in the event that surface films are retained on the workpiece. At present, the only way of selecting such cutting fluids is to choose them on the basis of extensive laboratory tests and/or service experience. An alternative is to provide unusual care in washing the cutting fluid away after machining with due consideration given to the difficulties of washing complex finished assemblies.

Cutting fluid selection can have a dramatic impact on the distortion and the residual stresses generated by grinding. Grinding is commonly done with water-miscible fluids, with oils or even dry. The differences among them relate to thermal cooling action, lubricity and possibly some chemical action. Water-miscible fluids have greater cooling capability and less lubricity than the oils; however, they also impose a greater heat shock on the workpiece. Dry grinding conditions are not usually compatible with low stress grinding or high surface integrity. Lubrication is the most important function of the grinding fluid relative to control of residual stresses. Occasionally, data will show little difference between water-miscible fluids and oils; however, most of these tests involve higher infeed rates or higher wheel speeds. The effect of infeed is more pronounced and tends to overwhelm the effects of the fluids. Grinding oils become increasingly effective at wheel speeds below 4,000 feet per minute (20 m/s). It is apparent that grinding oils are superior for high integrity grinding.

Compatibility with Water

Water-miscible fluids must be compatible with the water in which they are mixed. Water quality is perhaps the most important single factor affecting fluid life. The chemistry and biology of the water have a strong impact on the cooling effectiveness and the life of the coolant. The best cooling action can be obtained from very fine emulsions, but such emulsions cannot be made with water that is high in either hardness or dissolved solids. Many things are affected by the hardness level or pH of the water, such as rate of biological growth, rust protection, evaporative effect, emulsion stability, and foaming. A high chloride or sulfate content can negate the rust protection that has been built into a coolant formulation. Hard water (over 200 ppm) can break some emulsions, resulting in scum formation that leads to many performance problems. Soft water (under 100 ppm) often produces excessive foam, especially under conditions of high agitation.

Compatibility with the Machine Tool

The cutting fluid must also be compatible with the machine tool in which it is being used. The use of water-miscible fluids with most machines causes few problems. Usually, the drive mechanisms and the feed mechanisms are some distance from the cutting zone, completely enclosed with their own lubrication system and adequately sealed against the ingress of water-containing cutting fluids. With some of the more complex machine tools, however, like automatic and semi-automatic lathes and gear cutting and broaching machines, water-miscible fluids cannot be used. Because many of these machines rely on a cutting fluid to lubricate moving parts near the cutting zone, the use of oils is mandatory. In other cases, problems have been experienced in preventing a water-miscible fluid from reaching drive mechanisms and, therefore, oils must also be used.

Acceptability

Another important consideration in selecting cutting fluids is acceptability to the operator. Fluids designed with the operator in mind will be clean to use, pleasant and safe to breathe, nontoxic and free from ingredients harsh to human skin. Bacterial growth in the coolant should be controllable before and during use. Fluid clarity makes it easier for the operator to see the work while it is being machined. A pleasant-smelling, generally clean, "nonsticky" fluid helps to make an operator's job more pleasant and productive.

APPLICATION OF CUTTING FLUIDS

The way in which a cutting fluid is applied has a considerable influence on tool life and on the machining operation in general. Although there are many extremely effective devices and systems for supplying fluids to the cutting area, special equipment is not generally necessary for good results.

16.1 Cutting Fluid Selection and Use

Even the best fluid, however, cannot perform its function unless it is effectively delivered to the cutting zone. Thus, a fluid chosen for its lubricating qualities must be directed so that it can form a film at the sliding surfaces. Likewise, a fluid used for cooling must gain reasonable access to the cutting edge of the tool. These conditions usually require that the fluid be forced into the cutting zone so that the heat can be removed as it is generated. Continuous application of the cutting fluid is preferable to intermittent application. Sporatic fluid application causes thermal cycling, which leads to the formation and propogation of microcracks in hard and brittle tool materials, such as carbides. Besides shortened tool life, intermittent fluid application can lead to irregular surface finishes.

A secondary advantage of proper fluid application is the efficient removal of chips. This also aids in prolonging tool life, since properly placed fluid nozzles can prevent blockage or packing of the chips in the flutes of milling cutters and drill bits.

Manual Application

Paste and solid lubricants are applied manually by brush or oilcan to the tool and to the workpiece, mainly in tapping. More recent developments include pressurized aerosol dispersants and foams which cling to the tool and workpiece.

Manual application is an effective method where a small number of holes are to be drilled or tapped on a machine that is not equipped with a coolant system. When two different operations are performed on the same machine, manual application may be used in conjunction with the flood cooling system of the machine. The flood cooling may be used for a drilling operation with a moderately active fluid, whereas a highly active cutting oil can be applied manually for a tapping operation that follows.

Flood Application

The most common method of applying fluids is to flood the tool and workpiece. A low-pressure pump delivers the cutting fluid through piping and valves to nozzles situated near the cutting zone. After flooding the cutting area, the fluid drains down over various parts of the machine into the chip pan where it flows to the sump of the coolant pump. The volume of the tank must be sufficient to allow time for cooling and for the settling of fine swarf and may require from five to fifty gallons or more depending on the type of machine. A course strainer on top of the collecting pan prevents larger chips from entering the tank and the fine strainer at the pump section. Important exceptions are grinding, honing, lapping and deep-hole boring machines where high-quality work depends upon removing the finer swarf and abrasive particles. Occasions arise when the inclusion of filtration equipment on other types of machines can avoid the gross contamination and overloading of the coolant with the metallic particles and help keep the fluid clean, thus prolonging its useful life.

Flood application of cutting fluids permits a continuous flow of fluid to the cutting zone and is efficient in flushing away chips. A copious stream of fluid should be applied so that the cutting tool edge and the work are completely enveloped. In addition to supplying an adequate amount of fluid to the cutting zone, a copious flow provides cooling action that prevents undue temperature rise. Proper cutting fluid application should not be neglected because of inadequate splash guards. Typical coolant flow requirements are given in table 16.1-2.

The geometry of flood application directly influences the effectiveness of cutting fluids. Nozzles should direct fluid flow so that fluid is not thrown off the workpiece or tool by centrifugal force. Two or more nozzles should be used—one for directing fluid into the cutting zone and the other for auxiliary cooling and flushing away chips.

Turning and Boring

Turning and boring operations require the cutting fluid to be directed to the cutting zone where the chips form. This provides good cooling action by enveloping the cutting tool edge and the workpiece. An empirical rule is that the coolant nozzle should have an inside diameter of at least three-quarters the width of lathe-type cutting tools.

For heavy-duty turning and boring operations, a second nozzle supplying fluid from below and along the flank of the tool is desirable. The flow from the lower nozzle is not hindered by the chip and can be forced between the work and tool to help in providing lubrication at lower speeds.

Drilling and Reaming

For horizontal drilling and reaming, fluid application through hollow tools is preferable to external application because it provides adequate flow at the cutting edges and flushes chips out of the hole. Even in vertical drilling, very little fluid gets down to the cutting zone because the spiral flutes (which are designed to pump out the chips) pump out the fluid. The use of oil-hole drills will solve this problem.

Milling

Milling operations require the use of two nozzles directing a copious supply of fluid to both the incoming and the outgoing sides of the cutter. The fluid from one nozzle is pumped through the cutting zone by the cutter teeth, while fluid from the other nozzle washes away the chips as they emerge from the cutter. Standard round nozzles are sufficient for narrow cutters. Wide cutters require using fan-shaped nozzles at least three-quarters the width of the milling cutter to provide good coverage.

For face milling, use of a ring-type distributor consisting of a tube with many small holes can be beneficial. This directs the fluid at all cutting edges and keeps the cutter completely bathed in fluid to provide even cooling. When a particular size face mill is used often, the ring-type distributor can be supplemented with a special fan nozzle with a curved opening to match the cutter radius.

Grinding

A copious flow of cutting fluid at low pressures will generally provide good results for grinding operations. Where application of a large volume of fluid results in undue splashing, it is better to install splash guards on the machine than to reduce the coolant flow.

The normal methods of applying fluids to grinding operations remove little heat before it has dissipated into the mass of the workpiece. Because high surface speeds are in-

TABLE 16.1–2 Typical Coolant Flow Requirements

OPERATION	FLOW AT WORK	REMARKS
Turning	5 gal/min [19 L/min]/tool	
Screw Machining 1 inch [25 mm] dia 2 inch [50 mm] dia 3 inch [75 mm] dia.	 35 gal/min [132 L/min] 45 gal/min [170 L/min] 60 gal/min [227 L/min]	
Milling Small cutters Large cutters	 5 gal/min [19 L/min]/tool Up to 60 gal/min [227 L/min]/ tool	
Drilling, Reaming 1 inch [25 mm] dia. Drilling, Large	 2-3 gal/min [7.6-11 L/min] 2-3 gal/min x dia., inch [0.3-0.43 L/min x dia., mm]	
Gundrilling External chip removal type 0.18-0.37 inch [4.6-9.4 mm] dia. 0.37-0.75 inch [9.4-19 mm] dia. 0.75-1.25 inch [19-32 mm] dia. 1.25-1.50 inch [32-38 mm] dia. Internal chip removal type 0.31-0.37 inch [7.9-9.4 mm] dia. 0.37-0.75 inch [9.4-19 mm] dia 0.75-1.18 inch [19-30 mm] dia. 1.18-2.38 inch [30-60 mm] dia.	 2-6 gal/min [7.6-23 L/min] 5-17 gal/min [19-64 L/min] 10-40 gal/min [38-151 L/min] 17-50 gal/min [64-189 L/min] 5-8 gal/min [19-30 L/min] 8-26 gal/min [30-98 L/min] 26-66 gal/min [98-250 L/min] 66-130 gal/min [250-492 L/min]	 Fine filtration required. Use higher flow rates for deeper holes and the largest diameters in each range.
Trepanning External chip removal heads 2-3.5 inch [51-89 mm] dia. 3.5-6 inch [89-152 mm] dia. 6-8 inch [152-203 mm] dia. Internal chip removal heads 2.37-6 inch [60-152 mm] dia. 6-12 inch [152-305 mm] dia. 12-18 inch [305-457 mm] dia. 18-24 inch [457-610 mm] dia.	 8-48 gal/min [30-182 L/min] 16-80 gal/min [61-303 L/min] 32-104 gal/min [121-394 L/min] 110-215 gal/min [416-814 L/min] 215-340 gal/min [814-1,287 L/min] 340-460 gal/min [1,287-1,741 L/min] 460-570 gal/min [1,741-2,158 L/min]	 Fine filtration required. Use higher flow rates for deeper holes and the largest diameters in each range. If an emulsion is used instead of oil, increase the flow rate.
Honing Small Large	 3 gal/min [11 L/min]/hole 5 gal/min [19 L/min]/hole	 Very fine filtration required.
Broaching Small Large	 10 gal [38 L]/stroke 3 gal/stroke x length of cut, inch [0.45 L/stroke x length of cut, mm]	
Centerless grinding Small Large Other grinding	 20 gal/min [76 L/min] 40 gal/min [151 L/min] 5 gal/min/inch of wheel width [0.75 L/min/mm of wheel width]	 Fine filtration required.

volved, an entrained film of air usually encloses the grinding-wheel surface, and this prevents penetration of the fluid into the cutting zone. Special nozzles can be designed which will force the fluid through the air film and onto the wheel. These nozzles must be placed as close as possible to the workpiece to prevent complete loss of the fluid by the centrifugal forces of the wheel. Another method of overcoming the air film enclosing the grinding wheel is to use a close-fitting baffle that interrupts the air flow, creating a vacuum that sucks the grinding fluid into the wheel-work interface.

High-Pressure Application

For some operations, such as gundrilling and trepanning, high-pressure fluid systems are normally used with fluids being applied at pressures ranging from 100 to 2,000 psi [690 to 13,790 kPa]. A gundrilling tool is essentially a single-point end cutter similar to a boring tool, except that it has an internal passage for fluid. Trepanning is a hole-making operation that cuts a cylindrical path into the metal, leaving a solid core. This core passes through the hollow cylindrical cutting head as a tool feeds into the metal. The cutting fluid is pumped around the outside of the tool under pressure, forcing chips back through the center. Cutting fluids for trepanning must have good EP and anti-weld properties, must be low enough in viscosity to flow freely around the tool, and must have good oiliness.

Deep-hole drilling presents the problem of maintaining a sufficient flow of cutting fluid to the cutting edges. One solution is the use of oil-groove, oil-hole, or oil-tube drills, which utilize drill-flute space for cutting fluid passages. The fluid, under 50 to 100 psi [345 to 690 kPa] pressure, is transfered to the drill by a rotating gland and is forced directly into the cutting zone. The fluid flowing from the hole assists in chip removal. Oil-hole drills have become very popular in recent years, particularly for deep holes. Their use represents a significant improvement over flooding as the method of getting the cutting fluid to the drill lips. Significant increases in tool life and productivity can also be achieved (that is, oil-hole cooling gives better tool life at higher speeds than flood cooling does).

High-pressure systems are sometimes used for other operations. The high pressure facilitates the fluid's reaching the chip tool interface. In grinding, a high-pressure jet also serves to clean the wheel.

Mist Systems

Cutting fluids may also be applied in the form of an air-carried mist. Small jet equipment is used to disperse soluble oil or synthetic water-miscible cutting fluids as very fine droplets in a carrier such as air, at 10 to 80 psi [69 to 552 kPa], or occasionally as an aerosol. Water-miscible fluids are preferred over oil because oil presents possible health hazards and tends to clog. Mist application is best suited to operations where the cutting speed is high and the areas of cut are low, as in end milling. Cutting fluids normally chosen primarily for their cooling ability are used for mist application. The very small droplets come into contact with the hot tool, workpiece, or chip and evaporate and rapidly remove heat by vaporization. Mist cooling does not require the splash guards, the chip pans and the return hoses that are required for flood cooling. In addition, only small amounts of fluids are used, and these generally dry on the part or can be easily wiped away.

Mist systems are often advantageous because they:

- Provide better tool life than cutting dry
- Provide coolant when a flood system is not available or practical
- Apply fluids to otherwise inaccessible areas
- Provide higher fluid velocities at tool-workpiece interface than possible by flood cooling
- Reduce costs in some cases
- Give better visibility of the workpiece in cut

Disadvantages of mist systems include limited cooling capability and the need for venting.

Two types of mist generators are normally used—the aspirator type and the direct-pressure type. For the aspirator, a stream of air is blown over the open end of a tube which is immersed in the fluid. A partial vacuum is created and the fluid is drawn up the tube where it becomes entrained in the air stream. In the pressurized mist generator, either pressurized gas bottles or shop air may be used to force the fluid into the air stream.

Special Application Methods

Chilled cutting fluids and highly pressurized gases have been shown effective in increasing tool life. These methods are more exotic than the conventional application methods. In special cases they may be economically justifiable. They may prove worthwhile to try in cases where nothing else works.

MAINTENANCE OF CUTTING FLUIDS

Cutting fluids, like any other fluids that are used over and over again, must be cared for properly. There are several precautions that should be observed.

Cutting Oils

Oil-type fluids perform satisfactorily if applied at full flow to the tools and the work and if sufficient volume is maintained in the system to hold the oil temperature around 70° to 75°F [21° to 24°C].

Cutting and grinding oils become contaminated rapidly during use. Extraneous materials, chips, dirt, etc., should be removed continously or at periodic intervals by filters, strainers, centrifuges, or settling tanks. The mechanical edge-type filter, incorporating metal strips or disks as the filter element, acts principally as a strainer. The absorbent-type filter uses paper disks, cotton waste, or cloth bags as the filtering element. Magnetic filters are suitable for separation of ferrous particles. Centrifuging is used for removing heavy contaminants and particles from oil. Centrifug-

ing, together with a heating unit and settling tanks, is often used for extracting oil from chips.

All cutting oil systems should be drained at intervals, manually cleaned, flushed and replenished with filtered or new cutting oil. Frequency of cleaning depends upon individual conditions.

Emulsifiable Oils

Emulsions generally require more maintenance and care than do cutting oils. When preparing emulsions, always add the oil to at least two or three times as much water. This initial mix should be agitated thoroughly while the oil is being added; otherwise, soap forms which combines with the water causing the mineral oil to separate out. If not enough water is used, or if the water is added to the oil, an invert emulsion will result (water particles are dispersed in the oil phase) which is undesirable for metalcutting. Premixed fluids, instead of plain water, should be used for preparing or for alterating the mix concentration.

Water used in preparing emulsions is very important. Hard water containing various minerals and salts often hinders or impedes emulsification. It is not uncommon for emulsions made with hard water to "break" readily, that is, to separate into a stratified condition with a layer of oil or creamy emulsion floating on the surface. Such separation is detrimental. On the other hand, water that is too soft will cause foaming. Use of a specially formulated hard-water soluble oil with soft water may lead to the formation of a bluish-black stain on freshly ground ferrous parts.

Water used for making cutting fluid mixtures should be as pure as possible for the most economical and trouble-free use. Boiler water condensate (when available) or deionized water (mineral free) should be used. The deionizer removes all minerals by chemical absorption so that the effluent is equivalent to distilled water Consequently, no residues are left by evaporation of the water, and corrosion effects from minerals are eliminated.

Pretreatment of hard water is sometimes necessary. Water conditioning agents consisting usually of polyphosphate combinations are readily available, as is tri-sodium phosphate. The general rule for using these materials is to add about 1.5 ounces per 100 gallons [0.11 grams per liter] of water per grain of hardness. Chemical treatment of extremely hard water is far more economical than the purchase of a specially formulated soluble oil. Excessive use of polyphosphate water conditioners, however, will tend to increase bacteria, mold and fungi growth. Where water makeup rates are high, the use of deionized water is preferred.

Microorganisms in the water shorten the service life of a soluble-oil emulsion. Microorganisms of three types—bacteria, algae, and fungii—are often encountered in soluble oils, and all three have detrimental effects on emulsion stability. Many soluble oils are compounded with a bactericide, but the amount that can be added is limited by its solubility in the oil. When the emulsion is made, the bactericide is further diluted, reducing its effectiveness.

Rancidity, the term applied whenever a cutting fluid gives off a bad odor, is usually caused by bacterial growth. The rotten-egg stench emanating from the sump of a machine that has been shut down over a weekend is caused by bacteria that attack inorganic sulfates found in all natural waters. A quality cutting fluid and regular use of biocides where needed are the best insurance against rancidity.

Emulsion concentration is not always given the attention it deserves. In heavy-duty cutting operations, heat at the tool causes water to evaporate at a rate faster than the carryoff of oil on the machined parts. This results in an increased oil-to-water ratio, which if carried too far can cause an invert emulsion. The opposite applies to grinding operations where oil carryoff is higher and the emulsion becomes increasingly dilute with use. This may cause rusting unless the concentration is frequently checked and controlled.

The amount of time that an emulsion is kept in service varies widely—anywhere from one week to six months. Cooling an emulsion by mechanical circulation or refrigeration is useful in extending its service life and in producing better finish. Aeration, although an effective means of cooling an emulsion, will usually increase microorganism growth which results in reduced emulsion life. In use, emulsions should be held at a temperature between 55° and 70°F [13° and 21°C].

Before putting an emulsion into use, wash and flush the coolant system thoroughly. Deposits of all kinds must be removed. Emulsions are extremely susceptible to contamination If there is any reason to suspect that bacteria are present in the system, flush it with a germicidal solution before putting in the new emulsion.

Occupational Dermatitis

Dermatitis is not an affliction that must be tolerated. It can be closely controlled, or eliminated, by observing simple principles of cleanliness that the average person observes at home.

Dermatitis is frequently, though mistakenly, associated with the handling of petroleum products, particularly in the machine shop where the operator's hands or forearms are in prolonged contact with soluble oils and cutting oils. Combined with dirt, these fluids form grimy compounds that may become embedded in the skin, often blocking the pores and hair follicles. In many cases, these areas become infected and dermatitis sets in. This condition may occur with almost any material that is allowed to remain on the skin for a long period of time; it is not limited to petroleum products. A contributing factor may sometimes be the solvent action of the cutting fluid. Left on the skin, the fluid can dissolve the natural skin oils, inflaming the skin and causing it to crack.

The bactericides used in most cutting fluids generally have no effect on the incidence of dermatitis; however, formaldehyde-releasing bactericides may sensitize the skin of some people. People with thin skin are more susceptible to dermatitis. Fair, blond-complexioned people are usually more susceptible than are dark, oilier-skinned people. For hypersensitive workers, the only answer is a switch to another job—one in which they will not be exposed to cutting fluids.

16.1 Cutting Fluid Selection and Use

Maintaining personal cleanliness, keeping the fluid clean, using commercially available hand creams, barrier creams or protective clothing, and installing splash guards on the machines—all can help to control dermatitis in the shop.

Machine Cleaning Practice

For mineral-oil-base fluids, machine cleaning can generally be accomplished by periodic removal of chips, metal fines and sludge, followed by flushing with clean cutting oil.

No matter how effective a coolant clarifying system is on water-miscible fluids, machine cleaning must be performed eventually. Proper machine cleaning can extend coolant life 4 to 6 times, compared to simply removing the old coolant and replacing it with fresh coolant.

For machines not in operation, the proper cleaning procedure is as follows:

1. Pump out old coolant.
2. Clean out chips and oil residue.
3. Add cleaner mixed with water at a ratio of 1:50 to machine tool (fill reservoir).
4. Circulate cleaner for at least three hours until machine is clean and apply cleaning solution directly to all machine surfaces that are not in contact with circulating system.
5. When the machine is clean, pump out cleaner and remove all accumulated sediment from the sump.
6. Fill with enough plain water to circulate through all coolant lines and circulate for at least 15 minutes while rinsing surfaces previously cleaned in step 4.
7. Drain and refill with plain water, circulate, rinse and drain again.
8. Add new cutting fluid immediately to cover all exposed metal surfaces to prevent rusting.

By thoroughly cleaning a machine each time the coolant needs changing, all bacteria are removed and, consequently, are not present to immediately begin degrading the fresh coolant. Although a thorough cleaning takes considerably more time compared to pumping out and recharging, the coolant will last considerably longer; consequently, machines can be cleaned on a predetermined schedule instead of on a "catch-as-catch-can" program. The result is controllable machine downtime, which is always less expensive than emergency downtime.

Disposal of Cutting Fluids

Disposal problems with straight oil products are minimized with proper batch-type recovery equipment. Straight oil fluids can be sterilized and water contaminants removed by heat. Settling and addition of base concentrates usually restore adequate quality for continued use. When necessary, oil-base fluids should be disposed of by burning (possibly as a fuel).

In order to meet federal, state, and local water-pollution-control laws, all water-miscible cutting fluids should undergo some sort of treatment before disposal into a lake, stream, or municipal sewer system. The chemicals considered as pollutants in water-miscible products are oil, nitrites, phenols, phosphates, PCB, and heavy metals. The oil content can be broken out of emulsion by an acid or aluminum sulfate treatment. The nitrite content of the effluent can then be destroyed by treatment with sulfamic acid.

In some states effluent containing more than 2 parts per billion of phenol or phenolic derivatives is prohibited. Where regulations are less stringent, phenols can be removed by the use of a carbon filter or slurry.

Recycling Cutting Fluids

Recycling of cutting fluids can solve waste-disposal problems, reduce costs and ease pollution problems. A closed-loop system for cutting fluid recycling will have some loss, but 90 percent recovery is not unusual. Even lower rates of recovery can justify the expense of a closed-loop system.

One basic part of a recycling system is some kind of filter to remove metal chips and grinding swarf. Other elements are needed to remove tramp oils, to provide makeup fluid, and, unless the recycling system is part of a central fluid system, to haul, store, and pump fluid in and out of machine sumps.

A recycling system can be used for separate machines or used in a central fluid system as described in the following discussion.

CENTRAL FLUID SYSTEM

Wherever possible, consideration should be given to the possible use of central systems for handling of recycled fluids from groups of machines. This is only practical if the machines are using the same cutting fluid throughout. A group of grinding machines may be linked together to handle the swarf by means of an integrated conveying system; however, all the machines must be grinding similar materials since mixed metals lose their scrap value. The central collection of swarf wetted by cutting fluids also reduces physical handling and improves working conditions.

Centralized coolant systems enable a plant to better maintain cutting fluids by providing a convenient checkpoint with ancillary equipment to better maintain fluid concentration. A central system also means that more controls or checks can be brought into the evaluation by minimizing the number of samples that need to be checked. Besides providing better control, a central system minimizes maintenance with a fluid recycling system. Centralized systems usually cost less than a number of individual machine units.

One major advantage of the central system is its efficient removal of metal fines from the cutting fluid with the feasibility of removing tramp oil by centrifuge or by other means. Centrifuging has an additional benefit for the fluid user. By centrifuging the coolant, both the tramp oil and the metallic fines are removed. With removal of these con-

taminants, about half of the bacteria in the coolant is also removed, since bacteria tend to grow at the interfaces of the coolant solution and the tramp oil droplets and metallic fines. The continuous removal of these contaminants, periodic quality control tests, and the systematic use of additives or product concentrates based on these tests—are all major factors which make the central system an effective means of realizing extended cutting fluid life. Increased fluid life reduces the disposal problems inherent in the use of water-miscible fluids.

Extending cutting- or grinding-fluid life in central-system applications requires greater attention to fluid quality control. The large number of machine tools and the productivity involved justify greater levels of laboratory effort—not only to determine concentration but also to determine rancidity-control performance, corrosion protection, volume of recirculating chips (dirt load) and degree of unwanted contaminants. The use of system log records (water, product input, concentration, charge dates) and fluid test records (concentration, pH, bacteria count, dirt load, tramp oil, corrosion protection) are vital to monitoring the condition of the cutting fluid and can be useful for identifying corrective action.

ECONOMIC CONSIDERATIONS

The cost per piece produced is more important than the initial price of a cutting fluid because in many cases more expensive fluids may actually be more economical to use. Because the cutting fluid is part of a manufacturing system, an economic analysis of cutting fluids must take into consideration both the costs associated with the fluid itself and the costs affected by the fluid. These two cost divisions can be further subdivided into direct and indirect costs. In those cases where the influence of specific costs is great, it is possible to make a rough estimate of the savings without a complete cost analysis. In any event, the economic justification of cutting and grinding fluids should include not only the cost of the fluid but also its effect on the cost of tools, wheels, downtime, etc.

The selection of cutting fluids varies with the work material, the operations performed, etc. The benefits, such as reduced machining costs, increased production, decreased surface roughness, and greater accuracy, must be balanced against the costs of having too many different fluids. These include the cost of maintaining a large fluid inventory, fluid changing costs, fluid price differentials, and increased maintenance and disposal costs. Recycling of fluids can reduce the increasingly higher costs of fluid disposal.

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Cutting Fluid Recommendations 16.2

The following tables contain Cutting Fluid Recommendations for the machining operations and work materials listed in sections 1 thr ·h 8. The code numbers in these tables refer to the follc .g general types of fluids:

Code No.	Type
0	Dry
1	Oils–Light Duty (General Pur pose)
2	Oils–Medium Duty
3	Oils–Heavy Duty
4	Emulsifiable Oils–Light Duty (General Purpose)
5	Emulsifiable Oils–Heavy Duty
6	Chemicals and Synthetics–Light Duty (General Purpose)
7	Chemicals and Synthetics–Heavy Duty
8	Special–Light Duty
9	Special–Heavy Duty

For each general type of cutting fluid, the Cutting Fluid Key, section 16.3, provides an extensive list of cutting fluids by code number, type and trade name, and manufacturer. For each type of fluid, there are a number of subtypes, the choice of which has been left to the user because of the lack of more specific machining data.

All cutting fluids in section 16.3 are identified by specific trade name and by the manufacturer of the fluid. The Cutting Fluid Key includes all those companies who answered inquiries regarding the classification of their fluids and does not imply recommendation of particular fluids or manufacturers.

Example: Selection of a cutting fluid for peripheral end milling of an alloy steel (48-50 Rc).

Step 1. The Cutting Fluid Recommendations tables, section 16.2, indicate a preference for a Type 3 fluid which is an Oil–Heavy Duty. See page 16-22.

Step 2. The Cutting Fluid Key, section 16.3, lists the following subtypes under Oils–Heavy Duty (see pages 16-72 through 16-77):

Sulfurized Mineral Oil
Compounded Sulfurized Mineral Oil
Chlorinated Mineral Oil
Sulfurized Mineral Oil + Sulfur, Chlorine, and Phosphorus Compounding
Sulfo-Chlorinated Mineral Oil
Sulfurized Mineral Oil + Fatty Oil
Chlorinated Mineral Oil + Fatty Oil
Sulfo-Chlorinated Mineral Oil + Fatty Oil
Compounded Sulfo-Chlorinated Mineral Oil + Fatty Oil
Sulfo-Chlorinated Fatty Oil
Sulfurized Fatty Oil
Mineral Oil + Added Fat, Sulfur, Chlorine, and Phosphorus Compounding

From the subtypes listed, select a specific product based on machine tool and workpiece characteristics, company policies concerning use of cutting fluids, availability of a fluid, preference for a particular cutting fluid supplier, economics, and other conditions.

16.2 Cutting Fluid Recommendations

OPERATION	TOOL MATERIAL OR ABRASIVE	1. Free Machining Carbon Steels, Wrought			2. Carbon Steels, Wrought		
		100 to 275 Bhn	275 to 425 Bhn	48 to 65 R_C	85 to 275 Bhn	275 to 425 Bhn	48 to 65 R_C
1.1 Turning, Single Point and Box Tools	HSS	1, 4, 6	2, 5, 7	3, 5, 7	1, 4, 6	2, 5, 7	3, 5, 7
	Carbide	0, 4, 6	0, 4, 6	0, 4, 6	0, 4, 6	0, 4, 6	0, 4, 6
1.3 Turning	Diamond	—	—	—	—	—	—
1.4 Turning, Cutoff and Form Tools	HSS	2, 5, 7	3, 5, 7	3, 5, 7	2, 5, 7	3, 5, 7	3, 5, 7
	Carbide	0, 4, 6	0, 4, 6	5, 7	0, 4, 6	0, 4, 6	5, 7
1.5 Threading, Single Point	HSS	2, 5	3, 6	3	2, 5	3, 6	3
	Carbide	1, 4, 6	1, 4, 6	1, 4, 6	1, 4, 6	1, 4, 6	1, 4, 6
1.6 Threading, Die	HSS	2, 5	3, 6	3	2, 5	3, 6	3
	Carbide	1, 4, 6	1, 4, 6	1, 4, 6	1, 4, 6	1, 4, 6	1, 4, 6
1.7 Hollow Milling	HSS	1, 4, 6	2, 5, 7	3	1, 4, 6	2, 5, 7	3
	Carbide	0, 4, 6	0, 4, 6	2, 5, 7	0, 4, 6	0, 4, 6	2, 5, 7
2.1 Face Milling	HSS	1, 4, 6	2, 5, 7	3	1, 4, 6	2, 5, 7	3
	Carbide	0, 1, 4	0, 1, 4	0, 2	0, 1, 4	0, 1, 4	0, 2
2.2 Face Milling	Diamond	—	—	—	—	—	—
2.4 Slab Milling	HSS	1, 4, 6	2, 5, 7	3	1, 4, 6	2, 5, 7	3
	Carbide	0, 4, 6	0, 4, 6	2	0, 4, 6	0, 4, 6	2
2.5 Side and Slot Milling—Arbor Mounted Cutters	HSS	1, 4, 6	2, 5, 7	3	1, 4, 6	2, 5, 7	3
	Carbide	0, 4, 6	0, 4, 6	2	0, 4, 6	0, 4, 6	2
2.6 End Milling—Peripheral	HSS	1, 4, 6	2, 5, 7	3	1, 4, 6	2, 5, 7	3
	Carbide	0, 4, 6	0, 4, 6	3	0, 4, 6	0, 4, 6	3
2.8 End Milling—Slotting	HSS	1, 4, 6	2, 5, 7	3	1, 4, 6	2, 5, 7	3
	Carbide	0, 4, 6	0, 4, 6	3	0, 4, 6	0, 4, 6	3
2.9 Thread Milling	HSS	2, 5, 7	3, 5, 7	3	2, 5, 7	3, 5, 7	3
3.1 Drilling	HSS	1, 4, 6	2, 5, 7	3	1, 4, 6	2, 5, 7	3
	Carbide	0, 4, 6	0, 4, 6	3	0, 4, 6	0, 4, 6	3
3.3 Oil-Hole or Pressurized-Coolant Drilling	HSS	1, 4, 6	1, 4, 6	3	1, 4, 6	1, 4, 6	3
	Carbide	4, 6	4, 6	2	4, 6	4, 6	2
3.4 Spade Drilling	HSS	1, 4, 6	1, 4, 6	3	1, 4, 6	1, 4, 6	3
	Carbide	0, 4, 6	0, 4, 6	2	0, 4, 6	0, 4, 6	2
3.5 Gundrilling	HSS	1, 4, 6	2, 5, 7	3	1, 4, 6	2, 5, 7	3
	Carbide	1, 4, 6	1, 4, 6	2, 3	1, 4, 6	1, 4, 6	2, 3
3.6 Pressure Coolant Reaming (Gun Reaming)	HSS	1, 5, 6	2, 6, 7	3	1, 5, 6	2, 6, 7	3
	Carbide	1, 4, 6	1, 4, 6	2, 5, 7	1, 4, 6	1, 4, 6	2, 5, 7
3.7 Reaming	HSS	1, 5, 6	2, 6, 7	3	1, 5, 6	2, 6, 7	3
	Carbide	1, 4, 6	1, 4, 6	2, 3	1, 4, 6	1, 4, 6	2, 3
3.9 Boring	HSS	1, 4, 6	2, 5, 7	3, 5, 7	1, 4, 6	2, 5, 7	3, 5, 7
	Carbide	0, 4, 6	0, 4, 6	2, 4, 6	0, 4, 6	0, 4, 6	2, 4, 6
3.11 Boring	Diamond	—	—	—	—	—	—
3.12 Counterboring and Spotfacing	HSS	1, 4, 6	2, 5, 7	3	1, 4, 6	2, 5, 7	3
	Carbide	0, 4, 6	0, 4, 6	3, 7	0, 4, 6	0, 4, 6	3, 7
3.13 Trepanning	HSS	1, 4, 6	2, 5, 7	3	1, 4, 6	2, 5, 7	3
	Carbide	1, 4, 6	1, 4, 6	2, 3	1, 4, 6	1, 4, 6	2, 3
3.14 Honing	—	80	80	90	80	80	90
3.15 Burnishing	—	1, 5, 7	2, 5, 7	—	1, 5, 7	2, 5, 7	—
4.1 Tapping	HSS	1, 5, 7	2, 5, 7	3	1, 5, 7	2, 5, 7	3

OPERATION	TOOL MATERIAL OR ABRASIVE	1. Free Machining Carbon Steels, Wrought			2. Carbon Steels, Wrought		
		100 to 275 Bhn	275 to 425 Bhn	48 to 65 R_C	85 to 275 Bhn	275 to 425 Bhn	48 to 65 R_C
5.1 Planing	HSS	1, 4, 6	2, 5, 7	3	1, 4, 6	2, 5, 7	3
	Carbide	0, 1, 4	0, 1, 4	2	0, 1, 4	0, 1, 4	2
5.2 Broaching	HSS	2, 5, 7	3, 5, 7	3	2, 5, 7	3, 5, 7	3
	Carbide	1, 4, 6	1, 4, 6	3	1, 4, 6	1, 4, 6	3
6.1 Power Hack Sawing	HSS	1, 4, 6	2, 5, 7	3	1, 4, 6	2, 5, 7	3
6.2 Power Band Sawing	HSS	1, 4, 6	2, 5, 7	3	1, 4, 6	2, 5, 7	3
6.4 Circular Sawing	HSS	1, 4, 6	2, 5, 7	3	2, 5, 7	3, 5, 7	3
6.5 Circular Sawing	Carbide	0, 1, 4	0, 1, 4	2, 3	1, 4, 6	2, 5, 7	2, 3
6.6 Abrasive Cutoff	—	1, 4, 6	1, 4, 6	3	1, 4, 6	2	3
7.1 Gear Hobbing	HSS	2, 5, 7	3, 5, 7	3	2, 5, 7	3, 5, 7	3
7.2 Gear Cutting, Straight and Spiral Bevel	HSS	2, 5, 7	3, 5, 7	3	2, 5, 7	3, 5, 7	3
7.3 Gear Shaping	HSS	2, 5, 7	3, 5, 7	3	2, 5, 7	3, 5, 7	3
7.4 Gear Shaving	HSS	2, 5, 7	3, 5, 7	3	2, 5, 7	3, 5, 7	3
7.5 Gear Grinding, Form	—	1, 4, 6	1, 4, 6	3	1, 4, 6	1, 4, 6	3
8.1 Surface Grinding—Horiz. Spdl., Recip. Table	—	4, 6	4, 6	3	1, 4, 6	2, 4, 6	3
8.2 Surface Grinding—Horiz. Spdl., Recip. Table	CBN	—	—	5, 4	—	—	5, 4
8.3 Surface Grinding—Horiz. Spdl., Recip. Table	Diamond	—	—	—	—	—	—
8.4 Surface Grinding—Vertical Spdl., Rotary Table	—	4, 6	4, 6	3	1, 4, 6	2, 4, 6	3
8.5 Cylindrical Grinding	—	4, 6	4, 6	3	1, 4, 6	2, 4, 6	3
8.6 Cylindrical Grinding	CBN	—	—	5, 4	—	—	5, 4
8.7 Cylindrical Grinding	Diamond	—	—	—	—	—	—
8.8 Internal Grinding	—	4, 6	4, 6	3	1, 4, 6	2, 4, 6	3
8.9 Internal Grinding	CBN	—	—	5, 4	—	—	5, 4
8.10 Internal Grinding	Diamond	—	—	—	—	—	—
8.11 Centerless Grinding	—	4, 6	4, 6	3	1, 4, 6	2, 4, 6	3
8.13 Abrasive Belt Grinding	—	0, 1, 4	0, 1, 4	1, 4, 6	0, 1, 4	0, 1, 4	1, 4, 6
8.14 Thread Grinding	—	1, 4, 6	1, 4, 6	3	1, 4, 6	2, 4, 6	3

16.2 Cutting Fluid Recommendations

OPERATION	TOOL MATERIAL OR ABRASIVE	3. Carbon and Ferritic Alloy Steels (High Temperature Service)			4. Free Machining Alloy Steels, Wrought		
		–	150 to 200 Bhn	–	150 to 275 Bhn	275 to 425 Bhn	45 to 65 R_C
1.1 Turning, Single Point and Box Tools	HSS		1, 4, 6		1, 4, 6	2, 5, 7	3, 5, 7
	Carbide		0, 4, 6		0, 4, 6	0, 4, 6	0, 4, 6
1.3 Turning	Diamond		–		–	–	–
1.4 Turning, Cutoff and Form Tools	HSS		2, 5, 7		2, 5, 7	2, 5, 7	2, 5, 7
	Carbide		0, 4, 6		0, 4, 6	5, 7	5, 7
1.5 Threading, Single Point	HSS		2, 5		2, 5	2, 5	3
	Carbide		1, 4, 6		1, 4, 6	1, 4, 6	1, 4, 6
1.6 Threading, Die	HSS		2, 5		2, 5	2, 5	3
	Carbide		1, 4, 6		1, 4, 6	1, 4, 6	1, 4, 6
1.7 Hollow Milling	HSS		1, 4, 6		1, 5, 7	2, 5, 7	3
	Carbide		0, 4, 6		0, 4, 6	1, 4, 6	2, 5, 7
2.1 Face Milling	HSS		1, 4, 6		1, 5, 7	2, 5, 7	3
	Carbide		0, 1, 4		0, 4, 6	0, 4, 6	0, 2
2.2 Face Milling	Diamond		–		–	–	–
2.4 Slab Milling	HSS		1, 4, 6		1, 4, 6	2, 5, 7	3
	Carbide		0, 4, 6		0, 4, 6	1, 4, 6	2
2.5 Side and Slot Milling—Arbor Mounted Cutters	HSS		1, 4, 6		1, 5, 7	2, 5, 7	3
	Carbide		0, 4, 6		0, 4, 6	1, 4, 6	2
2.6 End Milling—Peripheral	HSS		1, 4, 6		1, 4, 6	2, 5, 7	3
	Carbide		0, 4, 6		0, 4, 6	0, 4, 6	3
2.8 End Milling—Slotting	HSS		1, 4, 6		1, 4, 6	2, 5, 7	3
	Carbide		0, 4, 6		0, 4, 6	0, 4, 6	3
2.9 Thread Milling	HSS		2, 5, 7		2, 5, 7	3, 5, 7	3
3.1 Drilling	HSS		1, 4, 6		1, 4, 6	2, 5, 7	3
	Carbide		0, 4, 6		0, 4, 6	1, 5, 7	3
3.3 Oil-Hole or Pressurized-Coolant Drilling	HSS		1, 4, 6		1, 4, 6	1, 4, 6	3
	Carbide		4, 6		4, 6	4, 6	2
3.4 Spade Drilling	HSS		1, 4, 6		1, 4, 6	2, 5, 7	3
	Carbide		0, 4, 6		0, 4, 6	1, 5, 7	2
3.5 Gundrilling	HSS		1, 4, 6		1, 4, 6	2, 5, 7	3
	Carbide		1, 4, 6		1, 4, 6	2, 5, 7	2, 3
3.6 Pressure Coolant Reaming (Gun Reaming)	HSS		1, 5, 6		1, 4, 6	2, 5, 7	3
	Carbide		1, 4, 6		1, 4, 6	1, 4, 6	2, 5, 7
3.7 Reaming	HSS		1, 5. 6		1, 4, 6	2, 5, 7	3
	Carbide		1, 4, 6		1, 4, 6	1, 4, 6	2, 3
3.9 Boring	HSS		1, 4, 6		1, 4, 6	2, 5, 7	3, 5, 7
	Carbide		0, 4, 6		0, 4, 6	4, 6	2, 4, 6
3.11 Boring	Diamond		–		–	–	–
3.12 Counterboring and Spotfacing	HSS		1, 4, 6		2, 5, 6	2, 5, 7	3
	Carbide		0, 4, 6		0, 4, 6	1, 4, 6	3, 7
3.13 Trepanning	HSS		1, 4, 6		1, 4, 6	2, 5, 7	3
	Carbide		1, 4, 6		1, 4, 6	1, 5, 7	2, 3
3.14 Honing	–		80		80	80	90
3.15 Burnishing	–		1, 5, 7		1, 5, 7	2, 5, 7	–
4.1 Tapping	HSS		1, 5, 7		2, 5, 7	3, 5, 7	3

OPERATION	TOOL MATERIAL OR ABRASIVE	3. Carbon and Ferritic Alloy Steels, Wrought (Low Temperature Service)			4. Free Machining Alloy Steels, Wrought		
		—	150 to 200 Bhn		150 to 275 Bhn	275 to 425 Bhn	45 to 65 R_C
5.1 Planing	HSS		1, 4, 6		1, 4, 6	2, 5, 7	3
	Carbide		0, 1, 4		0, 4, 6	0, 4, 6	2
5.2 Broaching	HSS		2, 5, 7		2, 5, 7	3, 5, 7	3
	Carbide		1, 4, 6		1, 4, 6	1, 4, 6	3
6.1 Power Hack Sawing	HSS		1, 4, 6		1, 4, 6	2, 5, 7	3
6.2 Power Band Sawing	HSS		1, 4, 6		1, 4, 6	2, 5, 7	3
6.4 Circular Sawing	HSS		1, 4, 6		2, 5, 7	3, 5, 7	3
6.5 Circular Sawing	Carbide		0, 1, 4		1, 4, 6	2, 5, 7	2, 3
6.6 Abrasive Cutoff	—		1, 4, 6		1, 4, 6	2	3
7.1 Gear Hobbing	HSS		2, 5, 7		2, 5, 7	3, 5, 7	3
7.2 Gear Cutting, Straight and Spiral Bevel	HSS		2, 5, 7		2, 5, 7	3, 5, 7	3
7.3 Gear Shaping	HSS		2, 5, 7		2, 5, 7	3, 5, 7	3
7.4 Gear Shaving	HSS		2, 5, 7		2, 5, 7	3, 5, 7	3
7.5 Gear Grinding, Form	—		1, 4, 6		1, 4, 6	1, 4, 6	3
8.1 Surface Grinding—Horiz. Spdl., Recip. Table	—		4, 6		1, 4, 6	2, 4, 6	3
8.2 Surface Grinding—Horiz. Spdl., Recip. Table	CBN		—		—	—	5, 4
8.3 Surface Grinding—Horiz. Spdl., Recip. Table	Diamond		—		—	—	—
8.4 Surface Grinding—Vertical Spdl., Rotary Table	—		4, 6		1, 4, 6	2, 4, 6	3
8.5 Cylindrical Grinding	—		4, 6		1, 4, 6	2, 4, 6	3
8.6 Cylindrical Grinding	CBN		—		—	—	5, 4
8.7 Cylindrical Grinding	Diamond		—		—	—	—
8.8 Internal Grinding	—		4, 6		1, 4, 6	2, 4, 6	3
8.9 Internal Grinding	CBN		—		—	—	5, 4
8.10 Internal Grinding	Diamond		—		—	—	—
8.11 Centerless Grinding	—		4, 6		1, 4, 6	2, 4, 6	3
8.13 Abrasive Belt Grinding	—		0, 1, 4		0, 1, 4	0, 1, 4	1, 4, 6
8.14 Thread Grinding	—		1, 4, 6		1, 4, 6	2, 4, 6	3

16.2 Cutting Fluid Recommendations

OPERATION	TOOL MATERIAL OR ABRASIVE	5. Alloy Steels, Wrought			6. High Strength Steels, Wrought		
		125 to 275 Bhn	275 to 425 Bhn	45 to 65 R_C	225 to 275 Bhn	275 to 425 Bhn	Over 45 R_C
1.1 Turning, Single Point and Box Tools	HSS	1, 4, 6	2, 5, 7	3, 5, 7	1, 4, 6	2, 5, 7	3, 5, 7
	Carbide	0, 4, 6	0, 4, 6	0, 4, 6	0, 4, 6	0, 4, 6	0, 4, 6
1.3 Turning	Diamond	—	—	—	—	—	—
1.4 Turning, Cutoff and Form Tools	HSS	2, 5, 7	2, 5, 7	2, 5, 7	2, 5, 7	2, 5, 7	2, 5, 7
	Carbide	0, 4, 6	5, 7	5, 7	0, 4, 6	5, 7	5, 7
1.5 Threading, Single Point	HSS	2, 5	2, 5	3	2, 5	2, 5	3
	Carbide	1, 4, 6	1, 4, 6	1, 4, 6	1, 4, 6	1, 4, 6	1, 4, 6
1.6 Threading, Die	HSS	2, 5	2, 5	3	2, 5	2, 5	3
	Carbide	1, 4, 6	1, 4, 6	1, 4, 6	1, 4, 6	1, 4, 6	1, 4, 6
1.7 Hollow Milling	HSS	1, 5, 7	2, 5, 7	3	1, 5, 7	2, 5, 7	3
	Carbide	0, 4, 6	1, 4, 6	2, 5, 7	0, 4, 6	1, 4, 6	2, 5, 7
2.1 Face Milling	HSS	1, 5, 7	2, 5, 7	3	1, 5, 7	2, 5, 7	3
	Carbide	0, 4, 6	0, 4, 6	0, 2	0, 4, 6	0, 4, 6	0, 2
2.2 Face Milling	Diamond	—	—	—	—	—	—
2.4 Slab Milling	HSS	1, 4, 6	2, 5, 7	3	1, 4, 6	2, 5, 7	3
	Carbide	0, 4, 6	1, 4, 6	2	0, 4, 6	1, 4, 6	2
2.5 Side and Slot Milling—Arbor Mounted Cutters	HSS	1, 5, 7	2, 5, 7	3	1, 5, 7	2, 5, 7	3
	Carbide	0, 4, 6	1, 4, 6	2	0, 4, 6	1, 4, 6	2
2.6 End Milling—Peripheral	HSS	1, 4, 6	2, 5, 7	3	1, 4, 6	2, 5, 7	3
	Carbide	0, 4, 6	0, 4, 6	3	0, 4, 6	0, 4, 6	3
2.8 End Milling—Slotting	HSS	1, 4, 6	2, 5, 7	3	1, 4, 6	2, 5, 7	3
	Carbide	0, 4, 6	0, 4, 6	3	0, 4, 6	0, 4, 6	3
2.9 Thread Milling	HSS	2, 5, 7	3, 5, 7	3	2, 5, 7	3, 5, 7	3
3.1 Drilling	HSS	1, 4, 6	2, 5, 7	3	1, 4, 6	2, 5, 7	3
	Carbide	0, 4, 6	1, 5, 7	3	0, 4, 6	1, 5, 7	3
3.3 Oil-Hole or Pressurized-Coolant Drilling	HSS	1, 4, 6	1, 4, 6	3	1, 4, 6	1, 4, 6	3
	Carbide	4, 6	4, 6	2	4, 6	4, 6	2
3.4 Spade Drilling	HSS	1, 4, 6	2, 5, 7	3	1, 4, 6	2, 5, 7	3
	Carbide	0, 4, 6	1, 5, 7	2	0, 4, 6	1, 5, 7	2
3.5 Gundrilling	HSS	1, 4, 6	2, 5, 7	3	1, 4, 6	2, 5, 7	3
	Carbide	1, 4, 6	2, 5, 7	2, 3	1, 4, 6	2, 5, 7	2, 3
3.6 Pressure Coolant Reaming (Gun Reaming)	HSS	1, 4, 6	2, 5, 7	3	1, 4, 6	2, 5, 7	3
	Carbide	1, 4, 6	1, 4, 6	2, 5, 7	1, 4, 6	1, 4, 6	2, 5, 7
3.7 Reaming	HSS	1, 4, 6	2, 5, 7	3	1, 4, 6	2, 5, 7	3
	Carbide	1, 4, 6	1, 4, 6	2, 3	1, 4, 6	1, 4, 6	2, 3
3.9 Boring	HSS	1, 4, 6	2, 5, 7	3, 5, 7	1, 4, 6	2, 5, 7	3, 5, 7
	Carbide	0, 4, 6	4, 6	2, 4, 6	0, 4, 6	4, 6	2, 4, 6
3.11 Boring	Diamond	—	—	—	—	—	—
3.12 Counterboring and Spotfacing	HSS	2, 5, 6	2, 5, 7	3	2, 5, 6	2, 5, 7	3
	Carbide	0, 4, 6	1, 4, 6	3, 7	0, 4, 6	1, 4, 6	3, 7
3.13 Trepanning	HSS	1, 4, 6	2, 5, 7	3	1, 4, 6	2, 5, 7	3
	Carbide	1, 4, 6	1, 5, 7	2, 3	1, 4, 6	1, 5, 7	2, 3
3.14 Honing	—	80	80	90	80	80	90
3.15 Burnishing	—	1, 5, 7	2, 5, 7	—	1, 5, 7	2, 5, 7	—
4.1 Tapping	HSS	2, 5, 7	3, 5, 7	3	2, 5, 7	3, 5, 7	3

OPERATION	TOOL MATERIAL OR ABRASIVE	5. Alloy Steels, Wrought			6. High Strength Steels, Wrought		
		125 to 275 Bhn	275 to 425 Bhn	45 to 65 R_C	225 to 275 Bhn	275 to 425 Bhn	Over 45 R_C
5.1 Planing	HSS	1, 4, 6	2, 5, 7	3	1, 4, 6	2, 5, 7	3
	Carbide	0, 4, 6	0, 4, 6	2	0, 4, 6	0, 4, 6	2
5.2 Broaching	HSS	2, 5, 7	3, 5, 7	3	2, 5, 7	3, 5, 7	3
	Carbide	1, 4, 6	1, 4, 6	3	1, 4, 6	1, 4, 6	3
6.1 Power Hack Sawing	HSS	1, 4, 6	2, 5, 7	3	1, 4, 6	2, 5, 7	3
6.2 Power Band Sawing	HSS	1, 4, 6	2, 5, 7	3	1, 4, 6	2, 5, 7	3
6.4 Circular Sawing	HSS	2, 5, 7	3, 5, 7	3	2, 5, 7	3, 5, 7	3
6.5 Circular Sawing	Carbide	1, 4, 6	2, 5, 7	2, 3	1, 4, 6	2, 5, 7	2, 3
6.6 Abrasive Cutoff	—	1, 4, 6	2	3	1, 4, 6	2	3
7.1 Gear Hobbing	HSS	2, 5, 7	3, 5, 7	3	2, 5, 7	3, 5, 7	3
7.2 Gear Cutting, Straight and Spiral Bevel	HSS	2, 5, 7	3, 5, 7	3	2, 5, 7	3, 5, 7	3
7.3 Gear Shaping	HSS	2, 5, 7	3, 5, 7	3	2, 5, 7	3, 5, 7	3
7.4 Gear Shaving	HSS	2, 5, 7	3, 5, 7	3	2, 5, 7	3, 5, 7	3
7.5 Gear Grinding, Form	—	1, 4, 6	1, 4, 6	3	1, 4, 6	1, 4, 6	3
8.1 Surface Grinding—Horiz. Spdl., Recip. Table	—	1, 4, 6	2, 4, 6	3	1, 4, 6	2, 4, 6	3
8.2 Surface Grinding—Horiz. Spdl., Recip. Table	CBN	—	—	5, 4	—	—	5, 4
8.3 Surface Grinding—Horiz. Spdl., Recip. Table	Diamond	—	—	—	—	—	—
8.4 Surface Grinding—Vertical Spdl., Rotary Table	—	1, 4, 6	2, 4, 6	3	1, 4, 6	2, 4, 6	3
8.5 Cylindrical Grinding	—	1, 4, 6	2, 4, 6	3	1, 4, 6	2, 4, 6	3
8.6 Cylindrical Grinding	CBN	—	—	5, 4	—	—	5, 4
8.7 Cylindrical Grinding	Diamond	—	—	—	—	—	—
8.8 Internal Grinding	—	1, 4, 6	2, 4, 6	3	1, 4, 6	2, 4, 6	3
8.9 Internal Grinding	CBN	—	—	5, 4	—	—	5, 4
8.10 Internal Grinding	Diamond	—	—	—	—	—	—
8.11 Centerless Grinding	—	1, 4, 6	2, 4, 6	3	1, 4, 6	2, 4, 6	3
8.13 Abrasive Belt Grinding	—	0, 1, 4	0, 1, 4	1, 4, 6	0, 1, 4	0, 1, 4	1, 4, 6
8.14 Thread Grinding	—	1, 4, 6	2, 4, 6	3	1, 4, 6	2, 4, 6	3

16.2 Cutting Fluid Recommendations

OPERATION	TOOL MATERIAL OR ABRASIVE	7. Maraging Steels, Wrought		8. Tool Steels, Wrought			
				Annealed		Hardened	
		275 to 425 Bhn	50 to 52 R_C	100 to 200 Bhn	200 to 325 Bhn	325 to 425 Bhn	45 to 65 R_C
1.1 Turning, Single Point and Box Tools	HSS	2, 5, 7	3, 5, 7	1, 4, 6	2, 5, 7	2, 5, 7	3, 5, 7
	Carbide	0, 4, 6	0, 4, 6	0, 4, 6	0, 4, 6	0, 4, 6	0, 4, 6
1.3 Turning	Diamond	—	—	—	—	—	—
1.4 Turning, Cutoff and Form Tools	HSS	2, 5, 7	2, 5, 7	2, 5, 7	2, 5, 7	2, 5, 7	3
	Carbide	5, 7	5, 7	2, 5, 7	5, 7	5, 7	5, 6, 7
1.5 Threading, Single Point	HSS	2, 5	3	3	3	3	3
	Carbide	1, 4, 6	1, 4, 6	2, 5, 7	2, 5, 7	1, 4, 6	1, 4, 6
1.6 Threading, Die	HSS	2, 5	3	3	3	3	3
	Carbide	1, 4, 6	1, 4, 6	2, 5, 7	2, 5, 7	1, 4, 6	1, 4, 6
1.7 Hollow Milling	HSS	2, 5	3	3	3	3	3
	Carbide	1, 4, 6	2, 5, 7	2, 5, 7	2, 5, 7	2, 5, 7	2, 5, 7
2.1 Face Milling	HSS	2, 5, 7	3	2, 5, 7	2, 5, 7	3	3
	Carbide	0, 4, 6	0, 2	0, 4, 6	0, 4, 6	0, 5, 7	0, 5, 7
2.2 Face Milling	Diamond	—	—	—	—	—	—
2.4 Slab Milling	HSS	2, 5, 7	3	2, 5, 7	2, 5, 7	3, 5, 7	3
	Carbide	1, 4, 6	2	1, 4, 6	1, 4, 6	2, 5, 7	3, 5, 7
2.5 Side and Slot Milling—Arbor Mounted Cutters	HSS	2, 5, 7	3	2, 5, 7	2, 5, 7	3	3
	Carbide	1, 4, 6	2	1, 4, 6	1, 4, 6	2, 5, 7	2, 5, 7
2.6 End Milling—Peripheral	HSS	2, 5, 7	3	2, 5, 7	2, 5, 7	3	3
	Carbide	0, 4, 6	?	1, 4, 6	1, 4, 6	2, 5, 7	3, 5, 7
2.8 End Milling—Slotting	HSS	2, 5, 7	3	2, 5, 7	2, 5, 7	3	3
	Carbide	0, 4, 6	3	1, 4, 6	1, 4, 6	2, 5, 7	3, 5, 7
2.9 Thread Milling	HSS	3, 5, 7	3	3	3	3	3
3.1 Drilling	HSS	2, 5, 7	3	2, 5, 7	2, 5, 7	3	3
	Carbide	1, 5, 7	3	1, 4, 6	1, 4, 6	2, 5, 7	3, 5, 7
3.3 Oil-Hole or Pressurized-Coolant Drilling	HSS	1, 4, 6	2	1, 4, 6	2, 5, 7	3	3
	Carbide	1, 4, 6	2	1, 4, 6	1, 4, 6	2, 5, 7	2, 5, 7
3.4 Spade Drilling	HSS	2, 5, 7	3	2, 5, 7	2, 5, 7	2, 5, 7	3
	Carbide	1, 5, 7	2	1, 4, 6	1, 4, 6	2, 5, 7	2
3.5 Gundrilling	HSS	2, 5, 7	3	3, 5, 7	2, 5, 7	2, 3	3
	Carbide	2, 5, 7	2, 3	2, 5, 7	2, 5, 7	2, 5, 7	3, 5, 7
3.6 Pressure Coolant Reaming (Gun Reaming)	HSS	2, 5, 7	3	2	3	3	3
	Carbide	1, 4, 6	2, 3	2, 5, 7	2, 5, 7	2, 5, 7	3, 5, 7
3.7 Reaming	HSS	2, 5, 7	3	3	3	3	3
	Carbide	1, 4, 6	2, 3	2, 4, 6	2, 4, 6	2, 5, 7	3, 5, 7
3.9 Boring	HSS	2, 5, 7	3, 5, 7	2, 5, 7	2, 5, 7	2, 5, 7	3, 5, 7
	Carbide	4, 6	2, 4, 6	1, 4, 6	1, 4, 6	2, 5, 7	2, 5, 7
3.11 Boring	Diamond	—	—	—	—	—	—
3.12 Counterboring and Spotfacing	HSS	2, 5, 7	3	2, 5, 7	2, 5, 7	3, 5, 7	3
	Carbide	1, 4, 6	3, 7	1, 4, 6	1, 4, 6	2, 5, 7	3, 5, 7
3.13 Trepanning	HSS	2, 5, 7	3	3, 5, 7	3, 5, 7	2, 3	3
	Carbide	1, 5, 7	2, 3	2, 5, 7	2, 5, 7	2, 5, 7	3, 5, 7
3.14 Honing		90	90	90	90	90	90
3.15 Burnishing	—	2, 5, 7	—	2	2	—	—
4.1 Tapping	HSS	3, 5, 7	3	3	3	3	3

OPERATION	TOOL MATERIAL OR ABRASIVE	7. Maraging Steels, Wrought		8. Tool Steels, Wrought			
				Annealed		Hardened	
		275 to 425 Bhn	50 to 52 R_C	100 to 200 Bhn	200 to 325 Bhn	325 to 425 Bhn	45 to 65 R_C
5.1 Planing	HSS	2, 5, 7	3	2, 5, 7	2, 5, 7	2, 5, 7	3
	Carbide	0, 4, 6	2	1, 4, 6	1, 4, 6	1, 5, 7	3, 5, 7
5.2 Broaching	HSS	3, 5, 7	3	2, 5, 7	2, 5, 7	3	3
	Carbide	2, 5, 7	3	1, 4, 6	1, 4, 6	3	3
6.1 Power Hack Sawing	HSS	2, 5, 7	3	1, 5, 7	1, 5, 7	3	3
6.2 Power Band Sawing	HSS	2, 5, 7	3	1, 5, 7	1, 5, 7	3	3
6.4 Circular Sawing	HSS	3, 5, 7	3	2, 5, 7	2, 5, 7	3	3
6.5 Circular Sawing	Carbide	2, 5, 7	3	1, 4, 6	1, 4, 6	2, 5, 7	3, 5, 7
6.6 Abrasive Cutoff	—	2	3	5, 7	5, 7	5, 7	5, 7
7.1 Gear Hobbing	HSS	3, 5, 7	3	2, 3	2, 3	3	3
7.2 Gear Cutting, Straight and Spiral Bevel	HSS	3, 5, 7	3	2, 3	2, 3	3	3
7.3 Gear Shaping	HSS	3, 5, 7	3	2, 3	2, 3	3	3
7.4 Gear Shaving	HSS	3, 5, 7	3	2, 3	2, 3	3	3
7.5 Gear Grinding, Form	—	1, 4, 6	3	5, 7	5, 7	2, 5, 7	2, 5, 7
8.1 Surface Grinding—Horiz. Spdl., Recip. Table	—	2, 4, 6	3	5, 7	5, 7	5, 7	5, 7
8.2 Surface Grinding—Horiz. Spdl., Recip. Table	CBN	—	5, 4	—	—	—	5, 4
8.3 Surface Grinding—Horiz. Spdl., Recip. Table	Diamond	—	—	—	—	—	5
8.4 Surface Grinding—Vertical Spdl., Rotary Table	—	2, 4, 6	3	5, 7	5, 7	5, 7	5, 7
8.5 Cylindrical Grinding	—	2, 4, 6	3	5, 7	5, 7	5, 7	5, 7
8.6 Cylindrical Grinding	CBN	—	5, 4	—	—	—	5, 4
8.7 Cylindrical Grinding	Diamond	—	—	—	—	—	—
8.8 Internal Grinding	—	2, 4, 6	3	5, 7	5, 7	5, 7	5, 7
8.9 Internal Grinding	CBN	—	5, 4	—	—	—	5, 4
8.10 Internal Grinding	Diamond	—	—	—	—	—	—
8.11 Centerless Grinding	—	2, 4, 6	3	5, 7	5, 7	5, 7	5, 7
8.13 Abrasive Belt Grinding	—	1, 4, 6	2, 5, 7	1, 5, 7	1, 5, 7	1, 5, 7	1, 5, 7
8.14 Thread Grinding	—	2, 4, 6	3	5, 7	5, 7	5, 7	5, 7

16.2 Cutting Fluid Recommendations

OPERATION	TOOL MATERIAL OR ABRASIVE	9. Nitriding Steels, Wrought		10. Armor Plate, Ship Plate & Aircraft Plate, Wrought		11. Structural Steels, Wrought	
		200 to 350 Bhn	60 to 65 R_C	200 to 350 Bhn	40 to 45 R_C	100 to 300 Bhn	Over 300 Bhn
1.1 Turning, Single Point and Box Tools	HSS	1, 4, 6	–	2, 5, 7	3, 5, 7	1, 4, 6	2, 5, 7
	Carbide	0, 4, 6	0, 4, 6	0, 4, 6	0, 4, 6	0, 4, 6	0, 4, 6
1.3 Turning	Diamond	–	–	–	–	–	–
1.4 Turning, Cutoff and Form Tools	HSS	2, 5, 7	–	2, 5, 7	2, 5, 7	2, 5, 7	2, 5, 7
	Carbide	4, 6	5, 7	5, 7	5, 7	0, 4, 6	5, 7
1.5 Threading, Single Point	HSS	3	–	3	3	2, 5	2, 5
	Carbide	1, 4, 6	1, 4, 6	1, 4, 6	1, 4, 6	1, 4, 6	1, 4, 6
1.6 Threading, Die	HSS	3	–	3	3	2, 5	2, 5
	Carbide	1, 4, 6	1, 4, 6	0, 4, 6	1, 4, 6	0, 4, 6	0, 4, 6
1.7 Hollow Milling	HSS	3	–	3	3	2, 5	2, 5
	Carbide	2, 5, 7	2, 5, 7	0, 4, 6	2, 5, 7	0, 4, 6	0, 4, 6
2.1 Face Milling	HSS	1, 4, 6	–	3, 5, 7	3	1, 5, 7	2, 5, 7
	Carbide	0, 4, 6	0, 2	0, 4, 6	0, 2	0, 4, 6	0, 4, 6
2.2 Face Milling	Diamond	–	–	–	–	–	–
2.4 Slab Milling	HSS	1, 4, 6	–	3, 5, 7	3	1, 4, 6	2, 5, 7
	Carbide	0, 4, 6	2	0, 4, 6	2	0, 4, 6	1, 4, 6
2.5 Side and Slot Milling—Arbor Mounted Cutters	HSS	1, 4, 6	–	3, 5, 7	3	1, 4, 6	2, 5, 7
	Carbide	0, 4, 6	2	0, 4, 6	2	0, 4, 6	1, 4, 6
2.6 End Milling—Peripheral	HSS	1, 4, 6	–	2, 5, 7	3	1, 4, 6	2, 5, 7
	Carbide	0, 4, 6	3	0, 4, 6	3	0, 4, 6	0, 4, 6
2.8 End Milling—Slotting	HSS	1, 4, 6	–	2, 5, 7	3	1, 4, 6	2, 5, 7
	Carbide	0, 4, 6	3	0, 4, 6	3	0, 4, 6	0, 4, 6
2.9 Thread Milling	HSS	2, 5, 7	–	7	3	2, 5, 7	3, 5, 7
3.1 Drilling	HSS	1, 4, 6	–	2, 5, 7	3	1, 4, 6	2, 5, 7
	Carbide	0, 4, 6	3	0, 4, 6	3	0, 4, 6	2, 5, 7
3.3 Oil-Hole or Pressurized-Coolant Drilling	HSS	1, 4, 6	–	2, 5, 7	3	1, 4, 6	2, 5, 7
	Carbide	4, 6	2	4, 6	2	4, 6	2, 5, 7
3.4 Spade Drilling	HSS	1, 4, 6	–	2, 5, 7	3	1, 4, 6	1, 4, 6
	Carbide	0, 4, 6	2	0, 4, 6	2	0, 4, 6	0, 4, 6
3.5 Gundrilling	HSS	1, 4, 6	–	2, 5, 7	3	1, 4, 6	2, 5, 7
	Carbide	1, 4, 6	2, 3	2, 5, 7	2, 3	1, 4, 6	2, 5, 7
3.6 Pressure Coolant Reaming (Gun Reaming)	HSS	1, 5, 7	–	2, 5, 7	3	1, 4, 6	2, 5, 7
	Carbide	1, 4, 6	2, 5, 7	1, 4, 6	2, 5, 7	1, 4, 6	1, 4, 6
3.7 Reaming	HSS	1, 4, 6	–	2, 5, 7	3	1, 4, 6	2, 5, 7
	Carbide	1, 4, 6	2, 3	1, 4, 6	2, 3	1, 4, 6	1, 4, 6
3.9 Boring	HSS	1, 4, 6	–	1, 4, 6	3, 5, 7	1, 4, 6	2, 5, 7
	Carbide	2, 4, 6	2, 4, 6	2, 4, 6	2, 4, 6	0, 4, 6	4, 6
3.11 Boring	Diamond	–	–	–	–	–	–
3.12 Counterboring and Spotfacing	HSS	2, 5, 7	–	2, 5, 7	3	2, 5, 6	2, 5, 7
	Carbide	4, 6	3, 7	1, 4, 6	3, 7	0, 4, 6	1, 4, 6
3.13 Trepanning	HSS	1, 4, 6	–	2, 5, 7	3	1, 4, 6	2, 5, 7
	Carbide	1, 4, 6	2, 3	2, 5, 7	2, 3	1, 4, 6	1, 5, 7
3.14 Honing	–	90	90	90	90	90	90
3.15 Burnishing	–	2	–	2	–	1, 4, 6	2, 5, 7
4.1 Tapping	HSS	2, 5, 7	--	3, 5, 7	3	2, 5, 7	3, 5, 7

OPERATION	TOOL MATERIAL OR ABRASIVE	9. Nitriding Steels, Wrought		10. Armor Plate, Ship Plate & Aircraft Plate, Wrought		11. Structural Steels, Wrought	
		200 to 350 Bhn	60 to 65 R_C	200 to 350 Bhn	40 to 45 R_C	100 to 300 Bhn	Over 300 Bhn
5.1 Planing	HSS	2, 5	—	2, 5, 7	3	1, 4, 6	2, 5, 7
	Carbide	4, 6	2	0, 4, 6	2	0, 4, 6	0, 4, 6
5.2 Broaching	HSS	2, 5, 7	3	3, 5, 7	3, 5, 7	2, 5, 7	2, 5, 7
	Carbide	4, 6	3	1, 5, 7	1, 5, 7	1, 5, 7	2, 5, 7
6.1 Power Hack Sawing	HSS	1, 4, 6	3	2, 5, 7	3, 5, 7	1, 4, 6	2, 5, 7
6.2 Power Band Sawing	HSS	1, 4, 3	3	2, 5, 7	3, 5, 7	1, 4, 6	2, 5, 7
6.4 Circular Sawing	HSS	2, 5, 7	3	3, 5, 7	3, 5, 7	1, 4, 6	3, 5, 7
6.5 Circular Sawing	Carbide	1, 4, 6	2, 3	1, 4, 6	1, 4, 6	1, 4, 6	2, 5, 7
6.6 Abrasive Cutoff	—	1, 4, 6	3	4, 6	4, 6	1, 4, 6	2
7.1 Gear Hobbing	HSS	2, 5, 7	3	7	7	2, 5, 7	3, 5, 7
7.2 Gear Cutting, Straight and Spiral Bevel	HSS	2, 5, 7	3	7	7	2, 5, 7	3, 5, 7
7.3 Gear Shaping	HSS	2, 5, 7	3	7	7	2, 5, 7	3, 5, 7
7.4 Gear Shaving	HSS	2, 5, 7	3	7	7	2, 5, 7	3, 5, 7
7.5 Gear Grinding, Form	—	2, 5, 7	3	2, 5	3, 5	1, 4, 6	1, 4, 6
8.1 Surface Grinding—Horiz. Spdl., Recip. Table	—	4, 6	3	4, 6	4, 6	1, 4, 6	2, 4, 6
8.2 Surface Grinding—Horiz. Spdl., Recip. Table	CBN	—	5, 4	—	—	—	—
8.3 Surface Grinding—Horiz. Spdl., Recip. Table	Diamond	—	—	—	—	—	—
8.4 Surface Grinding—Vertical Spdl., Rotary Table	—	4, 6	3	4, 6	4, 6	1, 4, 6	2, 4, 6
8.5 Cylindrical Grinding	—	4, 6	3	4, 6	4, 6	1, 4, 6	2, 4, 6
8.6 Cylindrical Grinding	CBN	—	5, 4	—	—	—	—
8.7 Cylindrical Grinding	Diamond	—	—	—	—	—	—
8.8 Internal Grinding	—	4, 6	3	4, 6	4, 6	1, 4, 6	2, 4, 6
8.9 Internal Grinding	CBN	—	5, 4	—	—	—	—
8.10 Internal Grinding	Diamond	—	—	—	—	—	—
8.11 Centerless Grinding	—	4, 6	3	4, 6	4, 6	1, 4, 6	2, 4, 6
8.13 Abrasive Belt Grinding	—	0, 1, 4	1, 4, 6	0, 1, 4	0, 1, 4	0, 1, 4	2, 5, 7
8.14 Thread Grinding	—	4, 6	3	7	7	1, 4, 6	2, 4, 6

16.2 Cutting Fluid Recommendations

OPERATION	TOOL MATERIAL OR ABRASIVE	12. Free Machining Stainless Steels, Wrought			13. Stainless Steels, Wrought		
					Ferritic and Austenitic		
		135 to 275 Bhn	Over 275 Bhn	—	135 to 275 Bhn	275 to 375 Bhn	—
1.1 Turning, Single Point and Box Tools	HSS	2, 5, 7	2, 5, 7		2, 5, 6	2, 5, 7	
	Carbide	0, 4, 6	0, 4, 6		0, 4, 6	0, 4, 6	
1.3 Turning	Diamond	—	—		—	—	
1.4 Turning, Cutoff and Form Tools	HSS	2, 5, 7	2, 5, 7		2, 5, 7	2	
	Carbide	1, 4, 6	1, 4, 6		4, 6	2, 5, 7	
1.5 Threading, Single Point	HSS	2, 5	2, 5		3	3	
	Carbide	1, 4, 6	1, 4, 6		2, 5, 7	2, 5, 7	
1.6 Threading, Die	HSS	2, 5	2, 5		3	3	
	Carbide	1, 4, 6	1, 4, 6		2, 5, 7	2, 5, 7	
1.7 Hollow Milling	HSS	2, 5	2, 5		3	3	
	Carbide	0, 4, 6	0, 4, 6		2, 5, 7	2, 5, 7	
2.1 Face Milling	HSS	1, 4, 6	1, 4, 6		2, 5, 7	2, 5, 7	
	Carbide	0, 4, 6	0, 4, 6		0, 4, 6	0, 4, 6	
2.2 Face Milling	Diamond	—	—		—	—	
2.4 Slab Milling	HSS	1, 4, 6	1, 4, 6		2, 5, 7	2, 5, 7	
	Carbide	1, 4, 6	1, 4, 6		1, 4, 6	1, 5, 7	
2.5 Side and Slot Milling—Arbor Mounted Cutters	HSS	1, 4, 6	1, 4, 6		2, 5, 7	2, 5, 7	
	Carbide	1, 4, 6	1, 4, 6		1, 4, 6	1, 5, 7	
2.6 End Milling—Peripheral	HSS	1, 4, 6	1, 4, 6		2, 5, 7	2, 5, 7	
	Carbide	0, 4, 6	0, 4, 6		0, 4, 6	0, 4, 6	
2.8 End Milling—Slotting	HSS	1, 4, 6	1, 4, 6		2, 5, 7	2, 5, 7	
	Carbide	0, 4, 6	0, 4, 6		0, 4, 6	0, 4, 6	
2.9 Thread Milling	HSS	2	2		3	3	
3.1 Drilling	HSS	1, 4, 6	1, 4, 6		2, 5, 7	2, 5, 7	
	Carbide	1, 4, 6	1, 4, 6		1, 4, 6	1, 5, 7	
3.3 Oil-Hole or Pressurized-Coolant Drilling	HSS	1, 4, 6	1, 4, 6		2, 5, 7	2, 5, 7	
	Carbide	1, 4, 6	1, 4, 6		1, 4, 6	1, 4, 6	
3.4 Spade Drilling	HSS	1, 4, 6	1, 4, 6		2, 5, 7	2, 5, 7	
	Carbide	1, 4, 6	1, 4, 6		1, 4, 6	1, 4, 6	
3.5 Gundrilling	HSS	2, 5, 7	2, 5, 7		2, 5, 7	2, 5, 7	
	Carbide	1, 4, 6	1, 4, 6		2, 5, 7	2, 5, 7	
3.6 Pressure Coolant Reaming (Gun Reaming)	HSS	2	2		3	3	
	Carbide	1, 4, 6	1, 4, 6		2, 5, 7	2, 5, 7	
3.7 Reaming	HSS	2	2		3	3	
	Carbide	1, 4, 6	1, 4, 6		2, 5, 7	2, 5, 7	
3.9 Boring	HSS	1, 5, 6	1, 5, 6		2, 5, 7	2, 5, 7	
	Carbide	0, 4, 6	0, 4, 6		1, 4, 6	2, 5, 7	
3.11 Boring	Diamond	—	—		—	—	
3.12 Counterboring and Spotfacing	HSS	1, 5, 6	1, 5, 6		2, 5, 7	2, 5, 7	
	Carbide	1, 4, 6	1, 4, 6		2, 5, 7	2, 5, 7	
3.13 Trepanning	HSS	3, 5, 7	3, 5, 7		3, 5, 7	3, 5, 7	
	Carbide	1, 4, 6	1, 4, 6		2, 5, 7	2, 5, 7	
3.14 Honing	—	90	90		90	90	
3.15 Burnishing	—	2	2		2	2	
4.1 Tapping	HSS	2	3		3	3	

OPERATION	TOOL MATERIAL OR ABRASIVE	12. Free Machining Stainless Steels, Wrought			13. Stainless Steels, Wrought		
					Ferritic and Austenitic		
		135 to 275 Bhn	Over 275 Bhn	—	135 to 275 Bhn	275 to 375 Bhn	—
5.1 Planing	HSS	1, 4, 6	1, 4, 6		2, 5, 7	2, 5, 7	
	Carbide	1, 4, 6	1, 4, 6		1, 4, 6	1, 4, 6	
5.2 Broaching	HSS	2, 5, 7	3		2, 5, 7	3	
	Carbide	1, 4, 6	2, 3		1, 4, 6	2, 3	
6.1 Power Hack Sawing	HSS	1, 5, 7	3, 5, 7		1 5, 7	3, 5, 7	
6.2 Power Band Sawing	HSS	1, 5, 7	3, 5, 7		1, 5, 7	3, 5, 7	
6.4 Circular Sawing	HSS	2, 5, 7	3, 5, 7		2, 5, 7	3, 5, 7	
6.5 Circular Sawing	Carbide	1, 4, 6	4, 6		1, 4, 6	4, 6	
6.6 Abrasive Cutoff	—	5, 7	2, 5, 7		5, 7	2, 5, 7	
7.1 Gear Hobbing	HSS	2, 3	2		2, 3	2	
7.2 Gear Cutting, Straight and Spiral Bevel	HSS	2, 3	2		2, 3	2	
7.3 Gear Shaping	HSS	2, 3	2		2, 3	2	
7.4 Gear Shaving	HSS	2, 3	2		2, 3	2	
7.5 Gear Grinding, Form	—	2, 3	2		5, 7	5, 7	
8.1 Surface Grinding—Horiz. Spdl., Recip. Table	—	5, 7	1, 4, 6		5, 7	5, 7	
8.2 Surface Grinding—Horiz. Spdl., Recip. Table	CBN	—	—		—	—	
8.3 Surface Grinding—Horiz. Spdl., Recip. Table	Diamond	—	—		—	—	
8.4 Surface Grinding—Vertical Spdl., Rotary Table	—	5, 7	1, 4, 6		5, 7	5, 7	
8.5 Cylindrical Grinding	—	5, 7	1, 4, 6		5, 7	5, 7	
8.6 Cylindrical Grinding	CBN	—	—		—	—	
8.7 Cylindrical Grinding	Diamond	—	—		—	—	
8.8 Internal Grinding	—	5, 7	1, 4, 6		5, 7	5, 7	
8.9 Internal Grinding	CBN	—	—		—	—	
8.10 Internal Grinding	Diamond	—	—		—	—	
8.11 Centerless Grinding	—	5, 7	1, 4, 6		5, 7	5, 7	
8.13 Abrasive Belt Grinding	—	0, 2, 5	0, 1, 4		0, 2, 5	0, 2, 5	
8.14 Thread Grinding	—	5, 7	5, 7		5, 7	5, 7	

16.2 Cutting Fluid Recommendations

OPERATION	TOOL MATERIAL OR ABRASIVE	13. Stainless Steels, Wrought			14. Precipitation Hardening Stainless Steels, Wrought		
		Martensitic					
		135 to 275 Bhn	275 to 425 Bhn	48 to 56 R_C	—	150 to 440 Bhn	—
1.1 Turning, Single Point and Box Tools	HSS	2, 5, 6	2, 5, 7	3, 5, 7		2, 5, 7	
	Carbide	0, 4, 6	0, 4, 6	0, 4, 6		0, 4, 6	
1.3 Turning	Diamond	—	—	—		—	
1.4 Turning, Cutoff and Form Tools	HSS	2, 5, 7	2	3		2	
	Carbide	4, 6	1, 5, 7	5, 6, 7		1, 5, 7	
1.5 Threading, Single Point	HSS	3	3	3		3	
	Carbide	2, 5, 7	1, 5, 7	2, 5, 7		1, 5, 7	
1.6 Threading, Die	HSS	3	3	3		3	
	Carbide	2, 5, 7	1, 5, 7	2, 5, 7		1, 5, 7	
1.7 Hollow Milling	HSS	2	2	3		2	
	Carbide	0, 1, 4, 6	1, 5, 7	2, 5, 7		1, 5, 7	
2.1 Face Milling	HSS	2, 5, 7	1, 5, 7	3		1, 5, 7	
	Carbide	0, 4, 6	0, 4, 6	0, 5, 7		0, 4, 6	
2.2 Face Milling	Diamond	—	—	—		—	
2.4 Slab Milling	HSS	2, 5, 7	2, 5, 7	3		2, 5, 7	
	Carbide	1, 4, 6	1, 5, 7	3, 5, 7		1, 5, 7	
2.5 Side and Slot Milling—Arbor Mounted Cutters	HSS	2, 5, 7	2, 5, 7	3		2, 5, 7	
	Carbide	1, 4, 6	1, 5, 7	2, 5, 7		1, 5, 7	
2.6 End Milling—Peripheral	HSS	2, 5, 7	2, 5, 7	3		2, 5, 7	
	Carbide	0, 4, 6	0, 4, 6	3, 5, 7		0, 4, 6	
2.8 End Milling—Slotting	HSS	2, 5, 7	2, 5, 7	3		2, 5, 7	
	Carbide	0, 4, 6	0, 4, 6	3, 5, 7		0, 4, 6	
2.9 Thread Milling	HSS	3	2	3		2	
3.1 Drilling	HSS	2, 5, 7	2	3		2	
	Carbide	1, 4, 6	1, 5, 7	3, 5, 7		1, 5, 7	
3.3 Oil-Hole or Pressurized-Coolant Drilling	HSS	2, 5, 7	2, 5, 7	3		2	
	Carbide	1, 4, 6	1, 4, 6	2, 5, 7		2, 5, 7	
3.4 Spade Drilling	HSS	2, 5, 7	2	3		2	
	Carbide	1, 4, 6	2, 5, 7	2, 5, 7		2, 5, 7	
3.5 Gundrilling	HSS	2, 5, 7	2	3		2	
	Carbide	2, 5, 7	2, 5, 7	3, 5, 7		1, 5, 7	
3.6 Pressure Coolant Reaming (Gun Reaming)	HSS	3	3	3		3	
	Carbide	2, 5, 7	2, 5, 7	3, 5, 7		2, 4, 6	
3.7 Reaming	HSS	3	3	3		3	
	Carbide	1, 5, 7	2, 5, 7	3, 5, 7		2, 4, 6	
3.9 Boring	HSS	2, 5, 7	2, 5, 7	3, 5, 7		2, 5, 7	
	Carbide	1, 4, 6	2	2, 5, 7		2	
3.11 Boring	Diamond	—	—	—		—	
3.12 Counterboring and Spotfacing	HSS	2, 5, 7	2, 5, 7	3		2, 5, 7	
	Carbide	2, 5, 7	2, 5, 7	3, 5, 7		2, 5, 7	
3.13 Trepanning	HSS	3, 5, 7	2	3		2	
	Carbide	2, 5, 7	2, 5, 7	3, 5, 7		2, 5, 7	
3.14 Honing	—	90	90	90		90	
3.15 Burnishing	—	2	2	2		2	
4.1 Tapping	HSS	3	2	3		2	

OPERATION	TOOL MATERIAL OR ABRASIVE	13. Stainless Steels, Wrought			14. Precipitation Hardening Stainless Steels, Wrought		
		Martensitic					
		135 to 275 Bhn	275 to 425 Bhn	48 to 56 R_C	—	150 to 440 Bhn	—
5.1 Planing	HSS	2, 5, 7	2, 5, 7	3		2, 5, 7	
	Carbide	1, 4, 6	0, 4, 6	3, 5, 7		0, 4, 6	
5.2 Broaching	HSS	2, 5, 7	3	3		3	
	Carbide	1, 4, 6	2, 3	3		2, 3	
6.1 Power Hack Sawing	HSS	1, 5, 7	3, 5, 7	3		3, 5, 7	
6.2 Power Band Sawing	HSS	1, 5, 7	3, 5, 7	3		3, 5, 7	
6.4 Circular Sawing	HSS	2, 5, 7	3, 5, 7	3		3, 5, 7	
6.5 Circular Sawing	Carbide	1, 4, 6	4, 6	3 5, 7		4, 6	
6.6 Abrasive Cutoff	—	5, 7	2, 5, 7	5, 7		2, 5, 7	
7.1 Gear Hobbing	HSS	2, 3	2	3		2	
7.2 Gear Cutting, Straight and Spiral Bevel	HSS	2, 3	2	3		2	
7.3 Gear Shaping	HSS	2, 3	2	3		2	
7.4 Gear Shaving	HSS	2, 3	2	3		2	
7.5 Gear Grinding, Form	—	5, 7	2	2, 5, 7		2	
8.1 Surface Grinding—Horiz. Spdl., Recip. Table	—	5, 7	1, 4, 6	5, 7		1, 4, 6	
8.2 Surface Grinding—Horiz. Spdl., Recip. Table	CBN	—	—	5, 4		—	
8.3 Surface Grinding—Horiz. Spdl., Recip. Table	Diamond	—	—	—		—	
8.4 Surface Grinding—Vertical Spdl., Rotary Table	—	5, 7	1, 4, 6	5, 7		1, 4, 6	
8.5 Cylindrical Grinding	—	5, 7	1, 4, 6	5, 7		1, 4, 6	
8.6 Cylindrical Grinding	CBN	—	—	5, 4		—	
8.7 Cylindrical Grinding	Diamond	—	—	—		—	
8.8 Internal Grinding	—	5, 7	1, 4, 6	5, 7		1, 4, 6	
8.9 Internal Grinding	CBN	—	—	5, 4		—	
8.10 Internal Grinding	Diamond	—	—	—		—	
8.11 Centerless Grinding	—	5, 7	1, 4, 6	5, 7		1, 4, 6	
8.13 Abrasive Belt Grinding	—	0, 1, 4	0, 1, 5	1, 5, 7		1, 5, 7	
8.14 Thread Grinding	—	5, 7	1, 4, 6	5, 7		1, 4, 6	

16.2 Cutting Fluid Recommendations

OPERATION	TOOL MATERIAL OR ABRASIVE	15. Carbon Steels, Cast			16. Alloy Steels, Cast		
		100 to 300 Bhn	Over 48 R_C	–	150 to 250 Bhn	250 to 400 Bhn	Over 48 R_C
1.1 Turning, Single Point and Box Tools	HSS	1, 4, 6	2, 5, 7		1, 4, 6	2, 5, 7	3, 5, 7
	Carbide	0, 4, 6	0, 4, 6		0, 4, 6	0, 4, 6	0, 4, 6
1.3 Turning	Diamond	–	–		–	–	–
1.4 Turning, Cutoff and Form Tools	HSS	2, 5, 7	3, 5, 7		2, 5, 7	2, 5, 7	2, 5, 7
	Carbide	0, 4, 6	0, 4, 6		0, 4, 6	5, 7	5, 7
1.5 Threading, Single Point	HSS	2, 5	3, 6		2, 5	2, 5	3
	Carbide	1, 4, 6	1, 4, 6		1, 4, 6	1, 4, 6	1, 4, 6
1.6 Threading, Die	HSS	2, 5	3, 6		2, 5	2, 5	3
	Carbide	1, 4, 6	1, 4, 6		1, 4, 6	1, 4, 6	1, 4, 6
1.7 Hollow Milling	HSS	1, 4, 6	2, 5, 7		1, 5, 7	2, 5, 7	3
	Carbide	0, 4, 6	0, 4, 6		0, 4, 6	1, 4, 6	2, 5, 7
2.1 Face Milling	HSS	1, 4, 6	2, 5, 7		1, 5, 7	2, 5, 7	3
	Carbide	0, 1, 4	0, 1, 4		0, 4, 6	0, 4, 6	0, 2
2.2 Face Milling	Diamond	–	–		–	–	–
2.4 Slab Milling	HSS	1, 4, 6	2, 5, 7		1, 4, 6	2, 5, 7	3
	Carbide	0, 4, 6	0, 4, 6		0, 4, 6	1, 4, 6	2
2.5 Side and Slot Milling—Arbor Mounted Cutters	HSS	., 4, 6	2, 5, 7		1, 5, 7	2, 5, 7	3
	Carbide	0, 4, 6	0, 4, 6		0, 4, 6	1, 4, 6	2
2.6 End Milling—Peripheral	HSS	1, 4, 6	2, 5, 7		1, 4, 6	2, 5, 7	3
	Carbide	0, 4, 6	0, 4, 6		0, 4, 6	0, 4, 6	3
2.8 End Milling—Slotting	HSS	1, 4, 6	2, 5, 7		1, 4, 6	2, 5, 7	3
	Carbide	0, 4, 6	0, 4, 6		0, 4, 6	0, 4, 6	3
2.9 Thread Milling	HSS	2, 5, 7	3, 5, 7		2, 5, 7	2, 5, 7	3
3.1 Drilling	HSS	1, 4, 6	2, 5, 7		1, 4, 6	2, 5, 7	3
	Carbide	0, 4, 6	0, 4, 6		0, 4, 6	1, 5, 7	3
3.3 Oil-Hole or Pressurized-Coolant Drilling	HSS	1, 4, 6	1, 4, 6		1, 4, 6	1, 4, 6	3
	Carbide	4, 6	4, 6		4, 6	4, 6	2
3.4 Spade Drilling	HSS	1, 4, 6	1, 4, 6		1, 4, 6	2, 5, 7	3
	Carbide	0, 4, 6	0, 4, 6		0, 4, 6	1, 5, 7	2
3.5 Gundrilling	HSS	1, 4, 6	2, 5, 7		1, 4, 6	2, 5, 7	3
	Carbide	1, 4, 6	1, 4, 6		1, 4, 6	2, 5, 7	2, 3
3.6 Pressure Coolant Reaming (Gun Reaming)	HSS	1, 5, 6	2, 6, 7		1, 4, 6	2, 5, 7	3
	Carbide	1, 4, 6	1, 4, 6		1, 4, 6	1, 4, 6	2, 5, 7
3.7 Reaming	HSS	1, 5, 6	2, 6, 7		1, 4, 6	2, 5, 7	3
	Carbide	1, 4, 6	1, 4, 6		1, 4, 6	1, 4, 6	2, 3
3.9 Boring	HSS	1, 4, 6	2, 5, 7		1, 4, 6	2, 5, 7	3, 5, 7
	Carbide	0, 4, 6	0, 4, 6		0, 4, 6	4, 6	2, 4, 6
3.11 Boring	Diamond	–	–		–	–	–
3.12 Counterboring and Spotfacing	HSS	1, 4, 6	2, 5, 7		2, 5, 6	2, 5, 7	3
	Carbide	0, 4, 6	0, 4, 6		0, 4, 6	1, 4, 6	3, 7
3.13 Trepanning	HSS	1, 4, 6	2, 5, 7		1, 4, 6	2, 5, 7	3
	Carbide	1, 4, 6	1, 4, 6		1, 4, 6	1, 5, 7	2, 3
3.14 Honing	–	80	80		80	80	90
3.15 Burnishing	–	1, 5, 7	2, 5, 7		1, 5, 7	2, 5, 7	–
4.1 Tapping	HSS	1, 5, 7	2, 5, 7		2, 5, 7	3, 5, 7	3

OPERATION	TOOL MATERIAL OR ABRASIVE	15. Carbon Steels, Cast			16. Alloy Steels, Cast		
		100 to 300 Bhn	Over 48 R_C	—	150 to 250 Bhn	250 to 400 Bhn	Over 48 R_C
5.1 Planing	HSS	1, 4, 6	2, 5, 7		1, 4, 6	2, 5, 7	3
	Carbide	0, 1, 4	0, 1, 4		0, 4, 6	0, 4, 6	2
5.2 Broaching	HSS	2, 5, 7	3		2, 5, 7	3, 5, 7	3
	Carbide	1, 4, 6	3		1, 4, 6	1, 4, 6	3
6.1 Power Hack Sawing	HSS	1, 4, 6	3		1, 4, 6	2, 5, 7	3
6.2 Power Band Sawing	HSS	1, 4, 6	3		1, 4, 6	2, 5, 7	3
6.4 Circular Sawing	HSS	2, 5, 7	3		2, 5, 7	3, 5, 7	3
6.5 Circular Sawing	Carbide	1, 4, 6	2, 3		1, 4, 6	2, 5, 7	2, 3
6.6 Abrasive Cutoff	—	1, 4, 6	3		1, 4, 6	2	3
7.1 Gear Hobbing	HSS	2, 5, 7	3		2, 5, 7	3, 5, 7	3
7.2 Gear Cutting, Straight and Spiral Bevel	HSS	2, 5, 7	3		2, 5, 7	3, 5, 7	3
7.3 Gear Shaping	HSS	2, 5, 7	3		2, 5, 7	3, 5, 7	3
7.4 Gear Shaving	HSS	2, 5, 7	3		2, 5, 7	3, 5, 7	3
7.5 Gear Grinding, Form	—	1, 4, 6	3		1, 4, 6	1, 4, 6	3
8.1 Surface Grinding—Horiz. Spdl., Recip. Table	—	1, 4, 6	3		1, 4, 6	2, 4, 6	3
8.2 Surface Grinding—Horiz. Spdl., Recip. Table	CBN	—	5, 4		—	—	5, 4
8.3 Surface Grinding—Horiz. Spdl., Recip. Table	Diamond	—	—		—	—	—
8.4 Surface Grinding—Vertical Spdl., Rotary Table	—	1, 4, 6	3		1, 4, 6	2, 4, 6	3
8.5 Cylindrical Grinding	—	1, 4, 6	3		1, 4, 6	2, 4, 6	3
8.6 Cylindrical Grinding	CBN	—	5, 4		—	—	5, 4
8.7 Cylindrical Grinding	Diamond	—	—		—	—	—
8.8 Internal Grinding	—	1, 4, 6	3		1, 4, 6	2, 4, 6	3
8.9 Internal Grinding	CBN	—	5, 4		—	—	5, 4
8.10 Internal Grinding	Diamond	—	—		—	—	—
8.11 Centerless Grinding	—	1, 4, 6	3		1, 4, 6	2, 4, 6	3
8.13 Abrasive Belt Grinding	—	0, 1, 4	1, 4, 6		0, 1, 4	0, 1, 4	1, 4, 6
8.14 Thread Grinding	—	1, 4, 6	3		1, 4, 6	2, 4, 6	3

16.2 Cutting Fluid Recommendations

OPERATION	TOOL MATERIAL OR ABRASIVE	17. Tool Steels, Cast				18. Stainless Steels, Cast	
						Austenitic and Ferritic	
		150 to 250 Bhn	325 to 375 Bhn	48 to 65 R_C	—	135 to 210 Bhn	—
1.1 Turning, Single Point and Box Tools	HSS	1, 4, 6	2, 5, 7	3, 5, 7		2, 5, 6	
	Carbide	0, 4, 6	0, 4, 6	0, 4, 6		0, 4, 6	
1.3 Turning	Diamond	—	—	—		—	
1.4 Turning, Cutoff and Form Tools	HSS	2, 5, 7	2, 5, 7	3		2, 5, 7	
	Carbide					4, 6	
1.5 Threading, Single Point	HSS	3	3	3		3	
	Carbide	2, 5, 7	1, 4, 6	1, 4, 6		2, 5, 7	
1.6 Threading, Die	HSS	3	3	3		3	
	Carbide	2, 5, 7	1, 4, 6	1, 4, 6		2, 5, 7	
1.7 Hollow Milling	HSS	3	3	3		3	
	Carbide	2, 5, 7	2, 5, 7	2, 5, 7		2, 5, 7	
2.1 Face Milling	HSS	2, 5, 7	3	3		2, 5, 7	
	Carbide	0, 4, 6	0, 5, 7	0, 5, 7		0, 4, 6	
2.2 Face Milling	Diamond	—	—	—		—	
2.4 Slab Milling	HSS	2, 5, 7	3, 5, 7	3		2, 5, 7	
	Carbide	1, 4, 6	2, 5, 7	3, 5, 7		1, 4, 6	
2.5 Side and Slot Milling—Arbor Mounted Cutters	HSS	2, 5, 7	3	3		2, 5, 7	
	Carbide	1, 4, 6	2, 5, 7	2, 5, 7		1, 4, 6	
2.6 End Milling—Peripheral	HSS	2, 5, 7	3	3		2, 5, 7	
	Carbide	1, 4, 6	2, 5, 7	3, 5, 7		0, 4, 6	
2.8 End Milling—Slotting	HSS	2, 5, 7	3	3		2, 5, 7	
	Carbide	1, 4, 6	2, 5, 7	3, 5, 7		0, 4, 6	
2.9 Thread Milling	HSS	3	3	3		3	
3.1 Drilling	HSS	2, 5, 7	3	3		2, 5, 7	
	Carbide	1, 4, 6	2, 5, 7	3, 5, 7		1, 4,	
3.3 Oil-Hole or Pressurized-Coolant Drilling	HSS	1, 4, 6	2, 5, 7	3		2, 5, 7	
	Carbide	1, 4, 6	2, 5, 7	2, 5, 7		1, 4, 6	
3.4 Spade Drilling	HSS	2, 5, 7	2, 5, 7	3		2, 5, 7	
	Carbide	1, 4, 6	2, 5, 7	2		1, 4, 6	
3.5 Gundrilling	HSS	3, 5, 7	2, 5, 7	3		2, 5, 7	
	Carbide	2, 5, 7	2, 5, 7	3, 5, 7		2, 5, 7	
3.6 Pressure Coolant Reaming (Gun Reaming)	HSS	2	3	3		3	
	Carbide	2, 5, 7	2, 5, 7	3, 5, 7		2, 5, 7	
3.7 Reaming	HSS	3	3	3		3	
	Carbide	2, 4, 6	2, 5, 7	3, 5, 7		2, 5, 7	
3.9 Boring	HSS	2, 5, 7	2, 5, 7	3, 5, 7		2, 5, 7	
	Carbide	1, 4, 6	2, 5, 7	2, 5, 7		1, 4, 6	
3.11 Boring	Diamond	—	—	—		—	
3.12 Counterboring and Spotfacing	HSS	2, 5, 7	3, 5, 7	3		2, 5, 7	
	Carbide	1, 4, 6	2, 5, 7	3, 5, 7		2, 5, 7	
3.13 Trepanning	HSS	3, 5, 7	2, 3	3		3, 5, 7	
	Carbide	2, 5, 7	2, 5, 7	3, 5, 7		2, 5, 7	
3.14 Honing	—	90	90	90		90	
3.15 Burnishing	—	2	2	—		2	
4.1 Tapping	HSS	3	3	3		3	

OPERATION	TOOL MATERIAL OR ABRASIVE	17. Tool Steels, Cast			18. Stainless Steels, Cast		
					Austenitic and Ferritic		
		150 to 250 Bhn	325 to 375 Bhn	48 to 65 R_C	—	135 to 210 Bhn	—
5.1 Planing	HSS	2, 5, 7	2, 5, 7	3		2, 5, 7	
	Carbide	1, 4, 6	1, 5, 7	3, 5, 7		1, 4, 6	
5.2 Broaching	HSS	2, 5, 7	3	3		2, 5, 7	
	Carbide	1, 4, 6	3	3		1, 4, 6	
6.1 Power Hack Sawing	HSS	1, 5, 7	3	3		1, 5, 7	
6.2 Power Band Sawing	HSS	1, 5, 7	3	3		1, 5, 7	
6.4 Circular Sawing	HSS	2, 5, 7	3	3		2, 5, 7	
6.5 Circular Sawing	Carbide	1, 4, 6	2, 5, 7	3, 5, 7		1, 4, 6	
6.6 Abrasive Cutoff	—	5, 7	5, 7	5, 7		5, 7	
7.1 Gear Hobbing	HSS	2, 3	3	3		2, 3	
7.2 Gear Cutting, Straight and Spiral Bevel	HSS	2, 3	3	3		2, 3	
7.3 Gear Shaping	HSS	2, 3	3	3		2, 3	
7.4 Gear Shaving	HSS	2, 3	3	3		2, 3	
7.5 Gear Grinding, Form	—	5, 7	2, 5, 7	2, 5, 7		5, 7	
8.1 Surface Grinding—Horiz. Spdl., Recip. Table	—	5, 7	5, 7	5, 7		5, 7	
8.2 Surface Grinding—Horiz. Spdl., Recip. Table	CBN	—	—	5, 4		—	
8.3 Surface Grinding—Horiz. Spdl., Recip. Table	Diamond	—	—	—		—	
8.4 Surface Grinding—Vertical Spdl., Rotary Table	—	5, 7	5, 7	5, 7		5, 7	
8.5 Cylindrical Grinding	—	5, 7	5, 7	5, 7		5, 7	
8.6 Cylindrical Grinding	CBN	—	—	5, 4		—	
8.7 Cylindrical Grinding	Diamond	—	—	—		—	
8.8 Internal Grinding	—	5, 7	5, 7	5, 7		5, 7	
8.9 Internal Grinding	CBN	—	—	5, 4		—	
8.10 Internal Grinding	Diamond	—	—	—		—	
8.11 Centerless Grinding	—	5, 7	5, 7	5, 7		5, 7	
8.13 Abrasive Belt Grinding	—	1, 5, 7	1, 5, 7	1, 5, 7		0, 2, 5	
8.14 Thread Grinding	—	5, 7	5, 7	5, 7		5, 7	

16.2 Cutting Fluid Recommendations

OPERATION	TOOL MATERIAL OR ABRASIVE	18. Stainless Steels, Cast			19. Precipitation Hardening Stainless Steels, Cast		
		Martensitic					
		135 to 275 Bhn	275 to 425 Bhn	–	–	325 to 460 Bhn	–
1.1 Turning, Single Point and Box Tools	HSS	2, 5, 6	2, 5, 7			2, 5, 7	
	Carbide	0, 4, 6	0, 4, 6			0, 4, 6	
1.3 Turning	Diamond	–	–			–	
1.4 Turning, Cutoff and Form Tools	HSS	2, 5, 7	2			2	
	Carbide	4, 6	1, 5, 7			1, 5, 7	
1.5 Threading, Single Point	HSS	3	3			3	
	Carbide	2, 5, 7	1, 5, 7			1, 5, 7	
1.6 Threading, Die	HSS	3	3			3	
	Carbide	2, 5, 7	1, 5, 7			1, 5, 7	
1.7 Hollow Milling	HSS	2	2			2	
	Carbide	0, 1, 4, 6	1, 5, 7			1, 5, 7	
2.1 Face Milling	HSS	2, 5, 7	1, 5, 7			1, 5, 7	
	Carbide	0, 4, 6	0, 4, 6			0, 4, 6	
2.2 Face Milling	Diamond	–	–			–	
2.4 Slab Milling	HSS	2, 5, 7	2, 5, 7			2, 5, 7	
	Carbide	1, 4, 6	1, 5, 7			1, 5, 7	
2.5 Side and Slot Milling—Arbor Mounted Cutters	HSS	2, 5, 7	2, 5, 7			2, 5, 7	
	Carbide	1, 4, 6	1, 5, 7			1, 5, 7	
2.6 End Milling—Peripheral	HSS	2, 5, 7	2, 5, 7			2, 5, 7	
	Carbide	0, 4, 6	0, 4, 6			0, 4, 6	
2.8 End Milling—Slotting	HSS	2, 5, 7	2, 5, 7			2, 5, 7	
	Carbide	0, 4, 6	0, 4, 6			0, 4, 6	
2.9 Thread Milling	HSS	3	2			2	
3.1 Drilling	HSS	2, 5, 7	2			2	
	Carbide	1, 4, 6	1, 5, 7			1, 5, 7	
3.3 Oil-Hole or Pressurized-Coolant Drilling	HSS	2, 5, 7	2, 5, 7			2	
	Carbide	1, 4, 6	1, 4, 6			2, 5, 7	
3.4 Spade Drilling	HSS	2, 5, 7	2			2	
	Carbide	1, 4, 6	2, 5, 7			2, 5, 7	
3.5 Gundrilling	HSS	2, 5, 7	2			2	
	Carbide	2, 5, 7	2, 5, 7			1, 5, 7	
3.6 Pressure Coolant Reaming (Gun Reaming)	HSS	3	3			3	
	Carbide	2, 5, 7	2, 5, 7			2, 4, 6	
3.7 Reaming	HSS	3	3			3	
	Carbide	1, 5, 7	2, 5, 7			2, 4, 6	
3.9 Boring	HSS	2, 5, 7	2, 5, 7			2, 5, 7	
	Carbide	1, 4, 6	2			2	
3.11 Boring	Diamond	–	–			–	
3.12 Counterboring and Spotfacing	HSS	2, 5, 7	2, 5, 7			2, 5, 7	
	Carbide	2, 5, 7	2, 5, 7			2, 5, 7	
3.13 Trepanning	HSS	3, 5, 7	2			2	
	Carbide	2, 5, 7	2, 5, 7			2, 5, 7	
3.14 Honing	–	90	90			90	
3.15 Burnishing	–	2	2			2	
4.1 Tapping	HSS	3	2			2	

OPERATION	TOOL MATERIAL OR ABRASIVE	18. Stainless Steels, Cast			19. Precipitation Hardening Stainless Steels, Cast		
		Martensitic					
		135 to 275 Bhn	275 to 425 Bhn	—	—	325 to 450 Bhn	—
5.1 Planing	HSS	2, 5, 7	2, 5, 7			2, 5, 7	
	Carbide	1, 4, 6	0, 4, 6			0, 4, 6	
5.2 Broaching	HSS	2, 5, 7	3			3	
	Carbide	1, 4, 6	2, 3			2, 3	
6.1 Power Hack Sawing	HSS	1, 5, 7	3, 5, 7			3, 5, 7	
6.2 Power Band Sawing	HSS	1, 5, 7	3, 5, 7			3, 5, 7	
6.4 Circular Sawing	HSS	2, 5, 7	3, 5, 7			3, 5, 7	
6.5 Circular Sawing	Carbide	1, 4, 6	4, 6			4, 6	
6.6 Abrasive Cutoff	—	5, 7	2, 5, 7			2, 5, 7	
7.1 Gear Hobbing	HSS	2, 3	2			2	
7.2 Gear Cutting, Straight and Spiral Bevel	HSS	2, 3	2			2	
7.3 Gear Shaping	HSS	2, 3	2			2	
7.4 Gear Shaving	HSS	2, 3	2			2	
7.5 Gear Grinding, Form	—	5, 7	2			2	
8.1 Surface Grinding—Horiz. Spdl., Recip. Table	—	5, 7	1, 4, 6			1, 4, 6	
8.2 Surface Grinding—Horiz. Spdl., Recip. Table	CBN	—	—			—	
8.3 Surface Grinding—Horiz. Spdl., Recip. Table	Diamond	—	—			—	
8.4 Surface Grinding—Vertical Spdl., Rotary Table	—	5, 7	1, 4, 6			1, 4, 6	
8.5 Cylindrical Grinding	—	5, 7	1, 4, 6			1, 4, 6	
8.6 Cylindrical Grinding	CBN	—	—			—	
8.7 Cylindrical Grinding	Diamond	—	—			—	
8.8 Internal Grinding	—	5, 7	1, 4, 6			1, 4, 6	
8.9 Internal Grinding	CBN	—	—			—	
8.10 Internal Grinding	Diamond	—	—			—	
8.11 Centerless Grinding	—	5, 7	1, 4, 6			1, 4, 6	
8.13 Abrasive Belt Grinding	—	0, 1, 4	0, 1, 5			1, 5, 7	
8.14 Thread Grinding	—	5, 7	1, 4, 6			1, 4, 6	

16.2 Cutting Fluid Recommendations

OPERATION	TOOL MATERIAL OR ABRASIVE	20. Austenitic Manganese Steels, Cast			21. Gray Cast Irons		
		–	150 to 220 Bhn	–	120 to 320 Bhn	45 to 60 R_C	–
1.1 Turning, Single Point and Box Tools	HSS		–		4, 6	–	
	Carbide		3, 5		0, 4, 6	–	
1.3 Turning	Diamond		–		–	–	
1.4 Turning, Cutoff and Form Tools	HSS		3, 5		4, 6	–	
	Carbide		3, 5		0, 4, 6	–	
1.5 Threading, Single Point	HSS		–		4, 6	–	
	Carbide		–		0, 4, 6	–	
1.6 Threading, Die	HSS		–		4, 6	–	
	Carbide		–		0, 4, 6	–	
1.7 Hollow Milling	HSS		–		5, 7	–	
	Carbide		3, 5		5, 7	–	
2.1 Face Milling	HSS		–		4, 6	–	
	Carbide		3, 5		0, 4, 6	–	
2.2 Face Milling	Diamond		–		–	–	
2.4 Slab Milling	HSS		–		4, 6	–	
	Carbide		–		0, 4, 6	–	
2.5 Side and Slot Milling—Arbor Mounted Cutters	HSS		–		4, 6	–	
	Carbide		3, 5		0, 4, 6	–	
2.6 End Milling—Peripheral	HSS		–		4, 6	–	
	Carbide		–		0, 4, 6	–	
2.8 End Milling—Slotting	HSS		–		4, 6	–	
	Carbide		–		0, 4, 6	–	
2.9 Thread Milling	HSS		–		4, 6	–	
3.1 Drilling	HSS		3, 5		4, 6	–	
	Carbide		3, 5		0, 4, 6	–	
3.3 Oil-Hole or Pressurized-Coolant Drilling	HSS		–		4, 6	–	
	Carbide		3, 5		4, 6	–	
3.4 Spade Drilling	HSS		–		4, 6	–	
	Carbide		3, 5		0, 4, 6	–	
3.5 Gundrilling	HSS		–		1, 86	–	
	Carbide		3, 5		1, 86	–	
3.6 Pressure Coolant Reaming (Gun Reaming)	HSS		–		4, 6	–	
	Carbide		–		4, 6	–	
3.7 Reaming	HSS		–		4, 6	–	
	Carbide		–		4, 6	–	
3.9 Boring	HSS		–		4, 6	–	
	Carbide		3, 5		0, 4, 6	–	
3.11 Boring	Diamond		–		–	–	
3.12 Counterboring and Spotfacing	HSS		–		4, 6	–	
	Carbide		3, 5		0, 4, 6	–	
3.13 Trepanning	HSS		–		1, 86	–	
	Carbide		–		1, 86	–	
3.14 Honing	–		–		80	–	
3.15 Burnishing	–		–		5, 7	–	
4.1 Tapping	HSS		–		4, 6	–	

OPERATION	TOOL MATERIAL OR ABRASIVE	20. Austenitic Manganese Steels, Cast			21. Gray Cast Irons		
		—	150 to 220 Bhn	—	120 to 320 Bhn	45 to 60 R_C	—
5.1 Planing	HSS		—		4, 6	—	
	Carbide		—		0, 4, 6	—	
5.2 Broaching	HSS		—		5, 7	—	
	Carbide		—		0, 4, 6	—	
6.1 Power Hack Sawing	HSS		3, 5		4, 6	—	
6.2 Power Band Sawing	HSS		3, 5		4, 6	—	
6.4 Circular Sawing	HSS		3, 5		4, 6	—	
6.5 Circular Sawing	Carbide		3, 5		0, 4, 6	—	
6.6 Abrasive Cutoff	—		3, 5		4, 6	—	
7.1 Gear Hobbing	HSS		—		4, 6	—	
7.2 Gear Cutting, Straight and Spiral Bevel	HSS		—		4, 6	—	
7.3 Gear Shaping	HSS		—		4, 6	—	
7.4 Gear Shaving	HSS		—		4, 6	—	
7.5 Gear Grinding, Form	—		—		4, 6	5, 7	
8.1 Surface Grinding—Horiz. Spdl., Recip. Table	—		3, 5		4, 6	5, 7	
8.2 Surface Grinding—Horiz. Spdl., Recip. Table	CBN		—		—	5, 4	
8.3 Surface Grinding—Horiz. Spdl., Recip. Table	Diamond		—		—	5	
8.4 Surface Grinding—Vertical Spdl., Rotary Table	—		3, 5		4, 6	5, 7	
8.5 Cylindrical Grinding	—		3, 5		4, 6	5, 7	
8.6 Cylindrical Grinding	CBN		—		—	5, 4	
8.7 Cylindrical Grinding	Diamond		—		—	—	
8.8 Internal Grinding	—		3, 5		4, 6	5, 7	
8.9 Internal Grinding	CBN		—		—	5, 4	
8.10 Internal Grinding	Diamond		—		—	—	
8.11 Centerless Grinding	—		3, 5		4, 6	5, 7	
8.13 Abrasive Belt Grinding	—		3, 5		0, 4, 6	0, 5, 7	
8.14 Thread Grinding	—		3, 5		4, 6	5, 7	

16.2 Cutting Fluid Recommendations

OPERATION	TOOL MATERIAL OR ABRASIVE	22. Compacted Graphite Cast Irons			23. Ductile Cast Irons		
		–	185 to 255 Bhn	–	120 to 400 Bhn	53 to 60 R_C	–
1.1 Turning, Single Point and Box Tools	HSS		4, 6		4, 6	–	
	Carbide		0, 4, 6		0, 4, 6	–	
1.3 Turning	Diamond		–		–	–	
1.4 Turning, Cutoff and Form Tools	HSS		4, 6		4, 6	–	
	Carbide		0, 4, 6		0, 4, 6	–	
1.5 Threading, Single Point	HSS		4, 6		4, 6	–	
	Carbide		0, 4, 6		0, 4, 6	–	
1.6 Threading, Die	HSS		4, 6		4, 6	–	
	Carbide		0, 4, 6		0, 4, 6	–	
1.7 Hollow Milling	HSS		5, 7		5, 7	–	
	Carbide		5, 7		5, 7	–	
2.1 Face Milling	HSS		4, 6		4, 6	–	
	Carbide		0, 4, 6		0, 4, 6	–	
2.2 Face Milling	Diamond		–		–	–	
2.4 Slab Milling	HSS		4, 6		4, 6	–	
	Carbide		0, 4, 6		0, 4, 6	–	
2.5 Side and Slot Milling—Arbor Mounted Cutters	HSS		4, 6		4, 6	–	
	Carbide		0, 4, 6		0, 4, 6	–	
2.6 End Milling—Peripheral	HSS		4, 5		4, 6	–	
	Carbide		0, 4, 6		0, 4, 6	–	
2.8 End Milling—Slotting	HSS		4, 6		4, 6	–	
	Carbide		0, 4, 6		0, 4, 6	–	
2.9 Thread Milling	HSS		4, 6		4, 6	–	
3.1 Drilling	HSS		4, 6		4, 6	–	
	Carbide		0, 4, 6		0, 4, 6	–	
3.3 Oil-Hole or Pressurized-Coolant Drilling	HSS		4, 6		4, 6	–	
	Carbide		4, 6		4, 6	–	
3.4 Spade Drilling	HSS		4, 6		4, 6	–	
	Carbide		0, 4, 6		0, 4, 6	–	
3.5 Gundrilling	HSS		1, 86		1, 86	–	
	Carbide		1, 86		1, 86	–	
3.6 Pressure Coolant Reaming (Gun Reaming)	HSS		4, 6		4, 6	–	
	Carbide		4, 6		4, 6	–	
3.7 Reaming	HSS		4, 6		4, 6	–	
	Carbide		4, 6		4, 6	–	
3.9 Boring	HSS		4, 6		4, 6	–	
	Carbide		0, 4, 6		0, 4, 6	–	
3.11 Boring	Diamond		–		–	–	
3.12 Counterboring and Spotfacing	HSS		4, 6		4, 6	–	
	Carbide		0, 4, 5		0, 4, 6	–	
3.13 Trepanning	HSS		1, 86		1, 86	–	
	Carbide		1, 86		1, 86	–	
3.14 Honing	–		80		80	–	
3.15 Burnishing	–		5, 7		5, 7	–	
4.1 Tapping	HSS		4, 6		4, 6	–	

OPERATION	TOOL MATERIAL OR ABRASIVE	22. Compacted Graphite Cast Irons			23. Ductile Cast Irons		
		–	185 to 255 Bhn	–	120 to 400 Bhn	53 to 60 R_C	–
5.1 Planing	HSS		4, 6		4, 6	–	
	Carbide		0, 4, 6		0,4,6	–	
5.2 Broaching	HSS		5, 7		5, 7	–	
	Carbide		0, 4, 6		0, 4, 6	–	
6.1 Power Hack Sawing	HSS		4, 6		4, 6	–	
6.2 Power Band Sawing	HSS		4, 6		4, 6	–	
6.4 Circular Sawing	HSS		4, 6		4, 6	–	
6.5 Circular Sawing	Carbide		0, 4, 6		0, 4, 6	0, 5, 7	
6.6 Abrasive Cutoff	–		4, 6		4, 6	5, 7	
7.1 Gear Hobbing	HSS		4, 6		4, 6	–	
7.2 Gear Cutting, Straight and Spiral Bevel	HSS		4, 6		4, 6	–	
7.3 Gear Shaping	HSS		4, 6		4, 6	–	
7.4 Gear Shaving	HSS		4, 6		4, 6	–	
7.5 Gear Grinding, Form	–		4, 6		4, 6	5, 7	
8.1 Surface Grinding—Horiz. Spdl., Recip. Table	–		4, 6		4, 6	5, 7	
8.2 Surface Grinding—Horiz. Spdl., Recip. Table	CBN		–		–	5, 4	
8 3 Surface Grinding—Horiz. Spdl., Recip. Table	Diamond		–		–	–	
8.4 Surface Grinding—Vertical Spdl., Rotary Table	–		4, 6		4, 6	5, 7	
8.5 Cylindrical Grinding	–		4, 6		4, 6	5, 7	
8.6 Cylindrical Grinding	CBN		–		–	5, 4	
8.7 Cylindrical Grinding	Diamond		–		–	–	
8.8 Internal Grinding	–		4, 6		4, 6	5, 7	
8.9 Internal Grinding	CBN		–		–	5, 4	
8.10 Internal Grinding	Diamond		–		–	--	
8.11 Centerless Grinding	–		4, 6		4, 6	5, 7	
8.13 Abrasive Belt Grinding	–		0, 4, 6		0, 4, 6	0, 5, 7	
8.14 Thread Grinding	–		4, 6		4, 6	5, 7	

16.2 Cutting Fluid Recommendations

OPERATION	TOOL MATERIAL OR ABRASIVE	24. Malleable Cast Irons			25. White Cast Irons (Abrasion Resistant)		
		110 to 260 Bhn	Over 52 R_C	—	—	450 to 600 Bhn	—
1.1 Turning, Single Point and Box Tools	HSS	4, 6	—			4, 6	
	Carbide	0, 4, 6	—			0, 4, 6	
1.3 Turning	Diamond	—	—			—	
1.4 Turning, Cutoff and Form Tools	HSS	4, 6	—			4, 6	
	Carbide	0, 4, 6	—			0, 4, 6	
1.5 Threading, Single Point	HSS	4, 6	—			—	
	Carbide	0, 4, 6	—			—	
1.6 Threading, Die	HSS	4, 6	—			—	
	Carbide	0, 4, 6	—			—	
1.7 Hollow Milling	HSS	5, 7	—			—	
	Carbide	5, 7	—			—	
2.1 Face Milling	HSS	4, 6	—			—	
	Carbide	0, 4, 6	—			0, 4, 6	
2.2 Face Milling	Diamond	—	—			—	
2.4 Slab Milling	HSS	4, 6	—			—	
	Carbide	0, 4, 6	—			—	
2.5 Side and Slot Milling—Arbor Mounted Cutters	HSS	4, 6	—			—	
	Carbide	0, 4, 6	—			0, 4, 6	
2.6 End Milling—Peripheral	HSS	4, 6	—			—	
	Carbide	0, 4, 6	—			0, 4, 6	
2.8 End Milling—Slotting	HSS	4, 6	—			—	
	Carbide	0, 4, 6	—			—	
2.9 Thread Milling	HSS	4, 6	—			—	
3.1 Drilling	HSS	4, 6	—			4, 6	
	Carbide	0, 4, 6	—			0, 4, 6	
3.3 Oil-Hole or Pressurized-Coolant Drilling	HSS	4, 6	—			4, 6	
	Carbide	4, 6	—			0, 4, 6	
3.4 Spade Drilling	HSS	4, 6	—			4, 6	
	Carbide	0, 4, 6	—			0, 4, 6	
3.5 Gundrilling	HSS	1, 86	—			—	
	Carbide	1, 86	—			—	
3.6 Pressure Coolant Reaming (Gun Reaming)	HSS	4, 6	—			—	
	Carbide	4, 6,	—			—	
3.7 Reaming	HSS	4, 6	—			4, 6	
	Carbide	4, 6	—			0, 4, 6	
3.9 Boring	HSS	4, 6	—			—	
	Carbide	0, 4, 6	—			0, 4, 6	
3.11 Boring	Diamond	—	—			—	
3.12 Counterboring and Spotfacing	HSS	4, 6	—			—	
	Carbide	0, 4, 6	—			0, 4, 6	
3.13 Trepanning	HSS	1, 86	—			—	
	Carbide	1, 86	—			—	
3.14 Honing	—	80	—			80	
3.15 Burnishing	—	5, 7	—			—	
4.1 Tapping	HSS	4, 6	—			4, 6	

OPERATION	TOOL MATERIAL OR ABRASIVE	24. Malleable Cast Irons			25. White Cast Irons (Abrasion Resistant)		
		110 to 260 Bhn	Over 52 R_C	—	—	450 to 600 Bhn	—
5.1 Planing	HSS	4, 6	—			—	
	Carbide	0, 4, 6	—			—	
5.2 Broaching	HSS	5, 7	—			—	
	Carbide	0, 4, 6	—			—	
6.1 Power Hack Sawing	HSS	4, 6	—			—	
6.2 Power Band Sawing	HSS	4, 6	—			—	
6.4 Circular Sawing	HSS	4, 6	—			—	
6.5 Circular Sawing	Carbide	0, 4, 6	0, 5, 7			0, 5, 7	
6.6 Abrasive Cutoff	—	4, 6	5, 7			5, 7	
7.1 Gear Hobbing	HSS	4, 6	—			—	
7.2 Gear Cutting, Straight and Spiral Bevel	HSS	4, 6	—			—	
7.3 Gear Shaping	HSS	4, 6	—			—	
7.4 Gear Shaving	HSS	4, 6	—			—	
7.5 Gear Grinding, Form	—	4, 6	5, 7			—	
8.1 Surface Grinding—Horiz. Spdl., Recip. Table	—	4, 6	5, 7			5, 7	
8.2 Surface Grinding—Horiz. Spdl., Recip. Table	CBN	—	5, 4			—	
8.3 Surface Grinding—Horiz. Spdl., Recip. Table	Diamond	—	—			—	
8.4 Surface Grinding—Vertical Spdl., Rotary Table	—	4, 6	5, 7			5, 7	
8.5 Cylindrical Grinding	—	4, 6	5, 7			5, 7	
8.6 Cylindrical Grinding	CBN	—	5, 4			—	
8.7 Cylindrical Grinding	Diamond	—	—			—	
8.8 Internal Grinding	—	4, 6	5, 7			5, 7	
8.9 Internal Grinding	CBN	—	5, 4			—	
8.10 Internal Grinding	Diamond	—	—			—	
8.11 Centerless Grinding	—	4, 6	5, 7			5, 7	
8.13 Abrasive Belt Grinding	—	0, 4, 6	0, 5, 7			0, 5, 7	
8.14 Thread Grinding	—	4, 6	5, 7			5, 7	

16.2 Cutting Fluid Recommendations

OPERATION	TOOL MATERIAL OR ABRASIVE	26. High Silicon Cast Irons			27. Chromium-Nickel Alloy Castings		
		–	52 R_C	–	–	275 to 375 Bhn (500 kg)	–
1.1 Turning, Single Point and Box Tools	HSS		–			3, 5, 7	
	Carbide		–			5, 7	
1.3 Turning	Diamond		–			–	
1.4 Turning, Cutoff and Form Tools	HSS		–			3, 5, 7	
	Carbide		–			5, 7	
1.5 Threading, Single Point	HSS		–			–	
	Carbide		–			–	
1.6 Threading, Die	HSS		–			–	
	Carbide		–			–	
1.7 Hollow Milling	HSS		–			–	
	Carbide		–			–	
2.1 Face Milling	HSS		–			3, 5, 7	
	Carbide		–			5, 7	
2.2 Face Milling	Diamond		–			–	
2.4 Slab Milling	HSS		–			–	
	Carbide		–			–	
2.5 Side and Slot Milling—Arbor Mounted Cutters	HSS		–			3, 5, 7	
	Carbide		–			5, 7	
2.6 End Milling—Peripheral	HSS		–			3, 5, 7	
	Carbide		–			5, 7	
2.8 End Milling—Slotting	HSS		–			3, 5, 7	
	Carbide		–			–	
2.9 Thread Milling	HSS		–			3, 5, 7	
3.1 Drilling	HSS		–			3, 5, 7	
	Carbide		–			–	
3.3 Oil-Hole or Pressurized-Coolant Drilling	HSS		–			3, 5, 7	
	Carbide		–			5, 7	
3.4 Spade Drilling	HSS		–			3, 5, 7	
	Carbide		–			–	
3.5 Gundrilling	HSS		–			–	
	Carbide		–			–	
3.6 Pressure Coolant Reaming (Gun Reaming)	HSS		–			–	
	Carbide		–			–	
3.7 Reaming	HSS		–			3, 5, 7	
	Carbide		–			5, 7	
3.9 Boring	HSS		–			3, 5, 7	
	Carbide		–			5, 7	
3.11 Boring	Diamond		–			–	
3.12 Counterboring and Spotfacing	HSS		–			3, 5, 7	
	Carbide		–			5, 7	
3.13 Trepanning	HSS		–			–	
	Carbide		–			–	
3.14 Honing	–		–			90	
3.15 Burnishing	–		–			–	
4.1 Tapping	HSS		–			2, 3	

OPERATION	TOOL MATERIAL OR ABRASIVE	26. High Silicon Cast Irons			27. Chromium-Nickel Alloy Castings		
		–	52 R_C	–	–	275 to 375 Bhn (500 kg)	–
5.1 Planing	HSS		–			–	
	Carbide		–			–	
5.2 Broaching	HSS		–			–	
	Carbide		–			–	
6.1 Power Hack Sawing	HSS		–			5 7, 3	
6.2 Power Band Sawing	HSS		–			5, 7, 3	
6.4 Circular Sawing	HSS		–			5, 7, 3	
6.5 Circular Sawing	Carbide		–			5, 7, 2	
6.6 Abrasive Cutoff	–		5, 7			5, 7	
7.1 Gear Hobbing	HSS		–			–	
7.2 Gear Cutting, Straight and Spiral Bevel	HSS		–			–	
7.3 Gear Shaping	HSS		–			–	
7.4 Gear Shaving	HSS		–			–	
7.5 Gear Grinding, Form	–		–			–	
8.1 Surface Grinding—Horiz. Spdl., Recip. Table	–		5, 7			2, 3	
8.2 Surface Grinding—Horiz. Spdl., Recip. Table	CBN		5, 4			–	
8.3 Surface Grinding—Horiz. Spdl., Recip. Table	Diamond		–			–	
8.4 Surface Grinding—Vertical Spdl., Rotary Table	–		5, 7			2, 3	
8.5 Cylindrical Grinding	–		5, 7			2, 3	
8.6 Cylindrical Grinding	CBN		5, 4			–	
8.7 Cylindrical Grinding	Diamond		–			–	
8.8 Internal Grinding	–		5, 7			2, 3	
8.9 Internal Grinding	CBN		5, 4			-	
8.10 Internal Grinding	Diamond		–			–	
8.11 Centerless Grinding	–		5, 7			2, 3	
8.13 Abrasive Belt Grinding	–		0, 5, 7			3	
8.14 Thread Grinding	–		5, 7			2, 3	

16.2 Cutting Fluid Recommendations

OPERATION	TOOL MATERIAL OR ABRASIVE	28. Aluminum Alloys, Wrought		29. Aluminum Alloys, Cast		30. Magnesium Alloys, Wrought	
		30 to 150 Bhn (500 kg)	—	40 to 125 Bnn (500 kg)	—	50 to 90 Bhn (500 kg)	—
1.1 Turning, Single Point and Box Tools	HSS	4, 6, 82		4, 6, 82		1, 88	
	Carbide	0, 4, 6		0, 4, 6		1, 88	
1.3 Turning	Diamond	0, 4, 6		0, 4, 6		1, 88	
1.4 Turning, Cutoff and Form Tools	HSS	4, 6, 82		4, 6, 82		1, 88	
	Carbide	0, 4, 6		0, 4, 6		1, 88	
1.5 Threading, Single Point	HSS	0, 1, 82		0, 1, 82		1, 88	
	Carbide	0, 1, 82		0, 1, 82		1, 88	
1.6 Threading, Die	HSS	0, 1, 82		0, 1, 82		1, 88	
	Carbide	0, 1, 82		0, 1 82		1, 88	
1.7 Hollow Milling	HSS	0, 1, 82		0, 1, 82		1, 88	
	Carbide	0, 1, 82		0, 1, 82		1, 88	
2.1 Face Milling	HSS	0, 1, 82		0, 1, 82		1, 88	
	Carbide	0, 1, 82		0, 1, 82		1, 88	
2.2 Face Milling	Diamond	0, 4, 6		0, 4, 6		1, 88	
2.4 Slab Milling	HSS	0, 1, 82		0, 1, 82		1, 88	
	Carbide	0, 1, 82		0, 1, 82		1, 88	
2.5 Side and Slot Milling—Arbor Mounted Cutters	HSS	0, 1, 82		0, 1, 82		1, 88	
	Carbide	0, 1, 82		0, 1, 82		1, 88	
2.6 End Milling—Peripheral	HSS	0, 1, 82		0, 1, 82		1, 88	
	Carbide	0, 1, 82		0, 1, 82		1, 88	
2.8 End Milling—Slotting	HSS	0, 1, 82		0, 1, 82		1, 88	
	Carbide	0, 1, 82		0, 1, 82		1, 88	
2.9 Thread Milling	HSS	0, 1, 82		0, 1, 82		1, 88	
3.1 Drilling	HSS	0, 1, 82		0, 1, 82		1, 88	
	Carbide	0, 1, 82		0, 1, 82		1, 88	
3.3 Oil-Hole or Pressurized-Coolant Drilling	HSS	1, 82		1, 82		1, 88	
	Carbide	1, 82		1, 82		1, 88	
3.4 Spade Drilling	HSS	1, 82		1, 82		1, 88	
	Carbide	0, 82		0, 82		88	
3.5 Gundrilling	HSS	1, 82		1, 82		1, 88	
	Carbide	1, 82		1, 82		1, 88	
3.6 Pressure Coolant Reaming (Gun Reaming)	HSS	1, 82		1, 82		1, 88	
	Carbide	1, 82		1, 82		1, 88	
3.7 Reaming	HSS	0, 1, 82		0, 1, 82		1, 88	
	Carbide	0, 1, 82		0, 1, 82		1, 88	
3.9 Boring	HSS	4, 6, 82		4, 6, 82		1, 88	
	Carbide	0, 4, 6		0, 4, 6		1, 88	
3.11 Boring	Diamond	0, 4, 6		0, 4, 6		1, 88	
3.12 Counterboring and Spotfacing	HSS	4, 6, 82		4, 6, 82		1, 88	
	Carbide	0, 4, 6		0, 4, 6		1, 88	
3.13 Trepanning	HSS	1, 82		1, 82		1, 88	
	Carbide	1, 82		1, 82		1, 88	
3.14 Honing	—	80		80		80	
3.15 Burnishing	—	1, 82		1, 82		—	
4.1 Tapping	HSS	0, 1, 82		0, 1, 82		1, 88	

OPERATION	TOOL MATERIAL OR ABRASIVE	28. Aluminum Alloys, Wrought		29. Aluminum Alloys, Cast		30. Magnesium Alloys, Wrought	
		30 to 150 Bhn (500 kg)	—	40 to 125 Bhn (500 kg)	—	50 to 90 Bhn (500 kg)	—
5.1 Planing	HSS	4, 6, 82		4, 6, 82		1, 88	
	Carbide	0, 4, 6		0, 4, 6		1, 88	
5.2 Broaching	HSS	4, 6, 82		4, 6, 82		0, 1, 88	
	Carbide	0, 4, 6		0, 4, 6		0, 1, 88	
6.1 Power Hack Sawing	HSS	0, 1, 82		0, 1, 82		0, 1, 88	
6.2 Power Band Sawing	HSS	0, 1, 82		0, 1, 82		0, 1, 88	
6.4 Circular Sawing	HSS	1, 82		1, 82		1, 88	
6.5 Circular Sawing	Carbide	0, 1, 82		0, 1, 82		0, 1, 88	
6.6 Abrasive Cutoff	—	1, 82		1, 82		0, 1, 88	
7.1 Gear Hobbing	HSS	1, 82		1, 82		0, 1, 88	
7.2 Gear Cutting, Straight and Spiral Bevel	HSS	1, 82		1, 82		1, 88	
7.3 Gear Shaping	HSS	1, 82		1, 82		0, 1, 88	
7.4 Gear Shaving	HSS	1, 82		1, 82		0, 1, 88	
7.5 Gear Grinding, Form	—	1, 82		1, 82		1, 88	
8.1 Surface Grinding—Horiz. Spdl., Recip. Table	—	1, 82		1, 82		1, 88	
8.2 Surface Grinding—Horiz. Spdl., Recip. Table	CBN	—		—		—	
8.3 Surface Grinding—Horiz. Spdl., Recip. Table	Diamond	—		—		—	
8.4 Surface Grinding—Vertical Spdl., Rotary Table	—	1, 82		1, 82		1, 88	
8.5 Cylindrical Grinding	—	1, 82		1, 82		1, 88	
8.6 Cylindrical Grinding	CBN	—		—		—	
8.7 Cylindrical Grinding	Diamond	—		—		—	
8.8 Internal Grinding	—	1, 82		1, 82		1, 88	
8.9 Internal Grinding	CBN	—		—		—	
8.10 Internal Grinding	Diamond	—		—		—	
8.11 Centerless Grinding	—	1, 82		1, 82		1, 88	
8.13 Abrasive Belt Grinding	—	1, 82		1, 82		1, 88	
8.14 Thread Grinding	—	1, 82		1, 82		1, 88	

16.2 Cutting Fluid Recommendations

OPERATION	TOOL MATERIAL OR ABRASIVE	31. Magnesium Alloys, Cast		32. Titanium Alloys, Wrought		33. Titanium Alloys, Cast	
		50 to 90 Bhn (500 kg)	—	110 to 440 Bhn	—	150 to 350 Bhn	—
1.1 Turning, Single Point and Box Tools	HSS	1, 88		83		33	
	Carbide	1, 88		0, 83		0 83	
1.3 Turning	Diamond	1, 88		—		—	
1.4 Turning, Cutoff and Form Tools	HSS	1, 88		83, 91		83, 91	
	Carbide	1, 88		83		83	
1.5 Threading, Single Point	HSS	1, 88		83, 91		83, 91	
	Carbide	1, 88		83		83	
1.6 Threading, Die	HSS	1, 88		83, 91		83, 91	
	Carbide	1, 88		83		83	
1.7 Hollow Milling	HSS	1, 88		83, 91		83, 91	
	Carbide	1, 88		83		83	
2.1 Face Milling	HSS	1, 88		83, 91		83, 91	
	Carbide	1, 88		0, 83		0, 83	
2.2 Face Milling	Diamond	1, 88		—		—	
2.4 Slab Milling	HSS	1, 88		83, 91		83, 91	
	Carbide	1, 88		83		83	
2.5 Side and Slot Milling—Arbor Mounted Cutters	HSS	1, 88		83, 91		83, 91	
	Carbide	1, 88		0, 83		83	
2.6 End Milling—Peripheral	HSS	1, 88		83, 91		83, 91	
	Carbide	1, 88		83		83	
2.8 End Milling—Slotting	HSS	1, 88		83, 91		83, 91	
	Carbide	1, 88		83		83	
2.9 Thread Milling	HSS	1, 88		83, 91		83, 91	
3.1 Drilling	HSS	1, 88		83, 91		83, 91	
	Carbide	1, 88		83		83	
3.3 Oil-Hole or Pressurized-Coolant Drilling	HSS	1, 88		83, 91		83, 91	
	Carbide	1, 88		83		83	
3.4 Spade Drilling	HSS	1, 88		83, 91		83, 91	
	Carbide	88		0, 83		0, 83	
3.5 Gundrilling	HSS	1, 88		83, 91		83, 91	
	Carbide	1, 88		83, 91		83, 91	
3.6 Pressure Coolant Reaming (Gun Reaming)	HSS	1, 88		83, 91		83, 91	
	Carbide	1, 88		83, 91		83, 91	
3.7 Reaming	HSS	1, 88		83, 91		83, 91	
	Carbide	1, 88		83, 91		83, 91	
3.9 Boring	HSS	1, 88		83, 91		83, 91	
	Carbide	1, 88		83, 91		93, 91	
3.11 Boring	Diamond	1, 88		—		—	
3.12 Counterboring and Spotfacing	HSS	1, 88		83, 91		83, 91	
	Carbide	1, 88		83		83	
3.13 Trepanning	HSS	1, 88		83, 91		83, 91	
	Carbide	1, 88		83		83	
3.14 Honing	—	80		90		90	
3.15 Burnishing	—	—		—		—	
4.1 Tapping	HSS	1, 88		1, 83		1, 83	

OPERATION	TOOL MATERIAL OR ABRASIVE	31. Magnesium Alloys, Cast		32. Titanium Alloys, Wrought		33. Titanium Alloys, Cast	
		50 to 90 Bhn (500 kg)	–	110 to 440 Bhn	–	150 to 350 Bhn	–
5.1 Planing	HSS	1, 88		83, 91		83, 91	
	Carbide	1, 88		83		83	
5.2 Broaching	HSS	0, 1, 88		83, 91		83, 91	
	Carbide	0, 1, 88		83, 91		83, 91	
6.1 Power Hack Sawing	HSS	0, 1, 88		83, 91		83, 91	
6.2 Power Band Sawing	HSS	0, 1, 88		83, 91		83, 91	
6.4 Circular Sawing	HSS	1, 88		83, 91		83, 91	
6.5 Circular Sawing	Carbide	0, 1, 88		83, 91		83, 91	
6.6 Abrasive Cutoff	–	0, 1, 88		81, 83		81, 83	
7.1 Gear Hobbing	HSS	0, 1, 88		1, 83		1, 83	
7.2 Gear Cutting, Straight and Spiral Bevel	HSS	1, 88		1, 83		1, 83	
7.3 Gear Shaping	HSS	0, 1, 88		1, 83		1, 83	
7.4 Gear Shaving	HSS	0, 1, 88		1, 83		1, 83	
7.5 Gear Grinding, Form	–	1, 88		81, 83		81, 83	
8.1 Surface Grinding—Horiz. Spdl., Recip. Table	–	1, 88		81, 83		81, 83	
8.2 Surface Grinding—Horiz. Spdl., Recip. Table	CBN	–		–		–	
8.3 Surface Grinding—Horiz. Spdl., Recip. Table	Diamond	–		–		–	
8.4 Surface Grinding—Vertical Spdl., Rotary Table	–	1, 88		81, 83		81, 83	
8.5 Cylindrical Grinding	–	1, 88		81, 83		81, 83	
8.6 Cylindrical Grinding	CBN	–		–		–	
8.7 Cylindrical Grinding	Diamond	–		–		–	
8.8 Internal Grinding	–	1, 88		81, 83		81, 83	
8.9 Internal Grinding	CBN	–		–		–	
8.10 Internal Grinding	Diamond	–		–		–	
8.11 Centerless Grinding	–	1, 88		81, 83		81, 83	
8.13 Abrasive Belt Grinding	–	1, 88		81, 83		81, 83	
8.14 Thread Grinding	–	1, 88		81, 83		81, 83	

16.2 Cutting Fluid Recommendations

OPERATION	TOOL MATERIAL OR ABRASIVE	34. Copper Alloys, Wrought		35. Copper Alloys, Cast		36. Nickel Alloys, Wrought and Cast	
		10 to 100 R_B	—	40 to 425 Bhn	—	80 to 360 Bhn	—
1.1 Turning, Single Point and Box Tools	HSS	4, 6, 87		4, 6, 87		3, 5, 7	
	Carbide	4, 6		4, 6		0, 5, 7	
1.3 Turning	Diamond	4, 6, 87		4, 6, 87		—	
1.4 Turning, Cutoff and Form Tools	HSS	4, 6, 87		4, 6, 87		3, 5, 7	
	Carbide	4, 6		4, 6		5, 7	
1.5 Threading, Single Point	HSS	1, 87		1, 87		3, 5, 7	
	Carbide	0, 1, 87		0, 1, 87		5, 7	
1.6 Threading, Die	HSS	1, 87		1, 87		3, 5, 7	
	Carbide	0, 1, 87		0, 1, 87		5, 7	
1.7 Hollow Milling	HSS	1, 87		1, 87		3, 5, 7	
	Carbide	0, 1, 87		0, 1, 87		2, 5, 7	
2.1 Face Milling	HSS	4, 6, 87		4, 6, 87		3, 5, 7	
	Carbide	4, 6		4, 6		0, 5, 7	
2.2 Face Milling	Diamond	4, 6, 87		4, 6, 87		—	
2.4 Slab Milling	HSS	4, 6, 87		4, 6, 87		3, 5, 7	
	Carbide	4, 6, 87		4, 6, 87		2, 5, 7	
2.5 Side and Slot Milling—Arbor Mounted Cutters	HSS	4, 6, 87		4, 6, 87		3, 5, 7	
	Carbide	4, 6, 87		4, 6, 87		2, 5, 7	
2.6 End Milling—Peripheral	HSS	4, 6, 87		4, 6, 87		3, 5, 7	
	Carbide	4, 6, 87		4, 6, 87		0, 5, 7	
2.8 End Milling—Slotting	HSS	4, 6, 87		4, 6, 87		3, 5, 7	
	Carbide	4, 6, 87		4, 6, 87		0, 5, 7	
2.9 Thread Milling	HSS	1, 87		1, 87		3, 5, 7	
3.1 Drilling	HSS	4, 6, 87		4, 6, 87		3, 5, 7	
	Carbide	4, 6, 87		4, 6, 87		0, 5, 7	
3.3 Oil-Hole or Pressurized-Coolant Drilling	HSS	4, 6, 87		4, 6, 87		3, 5, 7	
	Carbide	4, 6, 87		4, 6, 87		2, 5, 7	
3.4 Spade Drilling	HSS	4, 6, 87		4, 6, 87		3, 5, 7	
	Carbide	4, 6, 87		4, 6, 87		0, 5, 7	
3.5 Gundrilling	HSS	1, 86, 87		1, 86, 87		3, 5, 7	
	Carbide	1, 86, 87		1, 86, 87		2, 5, 7	
3.6 Pressure Coolant Reaming (Gun Reaming)	HSS	1, 87		1, 87		5, 7, 3	
	Carbide	1, 87		1, 87		5, 7, 2	
3.7 Reaming	HSS	1, 87		1, 87		5, 7, 3	
	Carbide	1, 87		1, 87		5, 7, 2	
3.9 Boring	HSS	4, 6, 87		4, 6, 87		5, 7, 3	
	Carbide	4, 6		4, 6		0, 5, 7	
3.11 Boring	Diamond	4, 6, 87		4, 6, 87		—	
3.12 Counterboring and Spotfacing	HSS	4, 6, 87		4, 6, 87		5, 7, 3	
	Carbide	4, 6		4, 6		5, 7, 2	
3.13 Trepanning	HSS	1, 86, 87		1, 86, 87		2, 86	
	Carbide	1, 86, 87		1, 86, 87		5, 7, 2	
3.14 Honing	—	80		80		90	
3.15 Burnishing	—	1, 87		1, 87		—	
4.1 Tapping	HSS	1, 87		1, 87		2, 3	

OPERATION	TOOL MATERIAL OR ABRASIVE	34. Copper Alloys, Wrought		35. Copper Alloys, Cast		36. Nickel Alloys, Wrought and Cast	
		10 to 100 R_B	–	40 to 425 Bhn	–	80 to 360 Bhn	–
5.1 Planing	HSS	4, 6, 87		4, 6, 87		5, 7, 3	
	Carbide	4, 6		4, 6		0, 5, 7	
5.2 Broaching	HSS	4, 6, 87		4, 6, 87		5, 7, 3	
	Carbide	4, 6, 87		4, 6, 87		5, 7, 3	
6.1 Power Hack Sawing	HSS	1, 87		1, 87		5, 7, 3	
6.2 Power Band Sawing	HSS	1, 87		1, 87		5, 7, 3	
6.4 Circular Sawing	HSS	4, 6, 87		4, 6, 87		5, 7, 3	
6.5 Circular Sawing	Carbide	1, 87		1, 87		5, 7, 2	
6.6 Abrasive Cutoff	–	1, 87		1, 87		5, 7	
7.1 Gear Hobbing	HSS	1 87		1, 87		–	
7.2 Gear Cutting, Straight and Spiral Bevel	HSS	1, 87		1, 87		–	
7.3 Gear Shaping	HSS	1, 87		1, 87		–	
7.4 Gear Shaving	HSS	1, 87		1, 87		–	
7.5 Gear Grinding, Form	–	1, 87		1, 87		–	
8.1 Surface Grinding—Horiz. Spdl., Recip. Table	–	1, 87		1, 87		2, 3	
8.2 Surface Grinding—Horiz. Spdl., Recip. Table	CBN	–		–		–	
8.3 Surface Grinding—Horiz. Spdl., Recip. Table	Diamond	4, 87		4, 87		–	
8.4 Surface Grinding—Vertical Spdl., Rotary Table	–	1, 87		1, 87		2, 3	
8.5 Cylindrical Grinding	–	1, 87		1, 87		2, 3	
8.6 Cylindrical Grinding	CBN	–		–		–	
8.7 Cylindrical Grinding	Diamond	4, 87		4, 87		–	
8.8 Internal Grinding	–	1, 87		1, 87		2, 3	
8.9 Internal Grinding	CBN	–		–		–	
8.10 Internal Grinding	Diamond	4, 87		4, 87		–	
8.11 Centerless Grinding	–	1, 87		1, 87		2, 3	
8.13 Abrasive Belt Grinding	–	1, 87		1, 87		3	
8.14 Thread Grinding	–	1, 87		1, 87		2, 3	

16.2 Cutting Fluid Recommendations

OPERATION	TOOL MATERIAL OR ABRASIVE	37. Beryllium Nickel Alloys, Wrought and Cast		38. Nitinol Alloys, Wrought		39. High Temperature Alloys, Wrought and Cast	
		200 to 425 Bhn	47 to 52 R_C	210 to 515 Bhn	–	140 to 475 Bhn	–
1.1 Turning, Single Point and Box Tools	HSS	3, 5, 7	–	2, 5 7		3, 5, 7	
	Carbide	5, 7	–	1, 4, 6		0, 4, 6	
1.3 Turning	Diamond	–	–	–		–	
1.4 Turning, Cutoff and Form Tools	HSS	3, 5, 7	–	3, 5, 7		3	
	Carbide	5, 7	–	2, 5, 7		3	
1.5 Threading, Single Point	HSS	3	–	3, 5, 7		3	
	Carbide	–	–	2, 4, 6		2, 5, 7	
1.6 Threading, Die	HSS	3, 5, 7	–	3, 5, 7		3	
	Carbide	–	–	2, 4, 6		2, 5, 7	
1.7 Hollow Milling	HSS	–	–	2, 3		3	
	Carbide	–	–	2		2, 5, 7	
2.1 Face Milling	HSS	3, 5, 7	–	2, 3		2, 5	
	Carbide	5, 7	–	2, 3		0, 3	
2.2 Face Milling	Diamond	–	–	–		–	
2.4 Slab Milling	HSS	3, 5, 7	–	–		3	
	Carbide	–	–	–		3	
2.5 Side and Slot Milling—Arbor Mounted Cutters	HSS	3, 5, 7	–	2, 3		3	
	Carbide	5, 7	–	2, 3		3	
2.6 End Milling—Peripheral	HSS	3, 5, 7	–	2, 3		3	
	Carbide	5, 7	–	2, 3		3	
2.8 End Milling—Slotting	HSS	3, 5, 7	–	2, 3		3	
	Carbide	–	–	2, 3		3	
2.9 Thread Milling	HSS	3, 5, 7	–	2, 3		3	
3.1 Drilling	HSS	3, 5, 7	–	2, 3		3	
	Carbide	–	–	2, 3		3	
3.3 Oil-Hole or Pressurized-Coolant Drilling	HSS	3, 5, 7	–	2, 3		3	
	Carbide	5, 7	–	2, 3		3	
3.4 Spade Drilling	HSS	3, 5, 7	–	2, 3		3	
	Carbide	–	–	2, 3		3	
3.5 Gundrilling	HSS	–	–	2, 3, 86		3	
	Carbide	5, 7	–	2, 3		3	
3.6 Pressure Coolant Reaming (Gun Reaming)	HSS	–	–	2, 3		3	
	Carbide	–	–	2, 3		3	
3.7 Reaming	HSS	3, 5, 7	–	2, 3		3	
	Carbide	5, 7	–	2, 3		3	
3.9 Boring	HSS	3, 5, 7	–	2, 5, 7		3, 5, 7	
	Carbide	5, 7	–	2, 5, 7		3	
3.11 Boring	Diamond	–	–	–		–	
3 12 Counterboring and Spotfacing	HSS	3, 5, 7	–	2, 5, 7		3	
	Carbide	5, 7	–	2, 5, 7		3	
3.13 Trepanning	HSS	3, 5, 7	–	2, 3, 86		3	
	Carbide	5, 7	–	2, 86		3	
3.14 Honing	–	90	–	90		90	
3.15 Burnishing	–	–	–	–		–	
4.1 Tapping	HSS	3, 94	–	2, 3		3	

OPERATION	TOOL MATERIAL OR ABRASIVE	37. Beryllium Nickel Alloys, Wrought and Cast		38. Nitinol Alloys, Wrought		39. High Temperature Alloys, Wrought and Cast	
		200 to 425 Bhn	47 to 52 R_C	210 to 515 Bhn	—	140 to 475 Bhn	—
5.1 Planing	HSS	—	—	—		—	
	Carbide	—	—	—		—	
5.2 Broaching	HSS	5, 3	—	—		3	
	Carbide	5, 7, 3	—	—		3	
6.1 Power Hack Sawing	HSS	5, 7, 3	—	2, 3		3	
6.2 Power Band Sawing	HSS	5, 7, 3	—	2, 3		3	
6.4 Circular Sawing	HSS	5, 7, 3	—	2, 3		3	
6.5 Circular Sawing	Carbide	5, 7, 2	5, 7, 2	2, 3		3	
6.6 Abrasive Cutoff	—	5, 7	5, 7	2, 3		5, 7	
7.1 Gear Hobbing	HSS	—	—	—		3	
7.2 Gear Cutting, Straight and Spiral Bevel	HSS	—	—	—		3	
7.3 Gear Shaping	HSS	—	—	—		3	
7.4 Gear Shaving	HSS	—	—	—		3	
7.5 Gear Grinding, Form	—	—	—	—		3	
8.1 Surface Grinding—Horiz. Spdl., Recip. Table	—	2, 3	2, 3	2, 3		3	
8.2 Surface Grinding—Horiz. Spdl., Recip. Table	CBN	—	—	—		5, 3	
8.3 Surface Grinding—Horiz. Spdl., Recip. Table	Diamond	—	—	—		—	
8.4 Surface Grinding—Vertical Spdl., Rotary Table	—	2, 3	2, 3	2, 3		3	
8.5 Cylindrical Grinding	—	2, 3	2, 3	2, 3		3	
8.6 Cylindrical Grinding	CBN	—	—	—		5, 3	
8.7 Cylindrical Grinding	Diamond	—	—	—		—	
8.8 Internal Grinding	—	2, 3	2, 3	2, 3		3	
8.9 Internal Grinding	CBN	—	—	—		5, 3	
8.10 Internal Grinding	Diamond	—	—	—		—	
8.11 Centerless Grinding	—	2, 3	2, 3	2, 3		3	
8.13 Abrasive Belt Grinding	—	3	3	2, 3		3	
8.14 Thread Grinding	—	2, 3	2, 3	2, 3		3	

16.2 Cutting Fluid Recommendations

OPERATION	TOOL MATERIAL OR ABRASIVE	40. Refractory Metals, Wrought, Cast and P/M		41. Zinc Alloys, Cast	42. Lead Alloys, Cast	43. Tin Alloys, Cast	44. Uranium, Wrought
		170 to 320 Bhn	--	80 to 100 Bhn	10 to 20 Bhn (500 kg)	15 to 30 Bhn (500 kg)	56 to 58 R_A
1.1 Turning, Single Point and Box Tools	HSS	3, 5		0, 4	–	–	4, 6
	Carbide	2, 5		0	–	–	4, 6
1.3 Turning	Diamond	–		–	–	–	–
1.4 Turning, Cutoff and Form Tools	HSS	3, 5		0, 4	–	–	4, 6
	Carbide	2, 5		0	–	–	4, 6
1.5 Threading, Single Point	HSS	–		0, 1, 4	–	–	4, 6
	Carbide	–		0, 1	–	–	4, 6
1.6 Threading, Die	HSS	–		0, 1, 4	–	–	4, 6
	Carbide	–		0, 1	–	–	4, 6
1.7 Hollow Milling	HSS	3, 5, 7		0, 1, 4	–	–	4, 6
	Carbide	2, 5, 7		0, 1	–	–	4, 6
2.1 Face Milling	HSS	2, 5		0 1	–	–	4, 6
	Carbide	2, 5		0	–	–	4, 6
2.2 Face Milling	Diamond	–		–	–	–	–
2.4 Slab Milling	HSS	3, 5		0, 1, 4	–	–	4, 6
	Carbide	–		0, 1	–	–	4, 6
2.5 Side and Slot Milling—Arbor Mounted Cutters	HSS	3, 5		0, 1, 4	–	–	4, 6
	Carbide	2, 5		0	–	–	4, 6
2.6 End Milling—Peripheral	HSS	2, 5		0, 1, 4	–	–	4, 6
	Carbide	5		0, 4	–	–	4, 6
2.8 End Milling—Slotting	HSS	2, 5		0, 1, 4	–	–	4, 6
	Carbide	5		0, 4	–	–	4, 6
2.9 Thread Milling	HSS	3		0, 1, 4	–	–	4, 6
3.1 Drilling	HSS	3		0, 1, 4	–	–	4, 6
	Carbide	2		0, 4	–	–	4, 6
3.3 Oil-Hole or Pressurized-Coolant Drilling	HSS	3		1, 4	–	–	4, 6
	Carbide	2		1, 4	–	–	4, 6
3.4 Spade Drilling	HSS	3		0, 1, 4	–	–	4, 6
	Carbide	2		0, 4	–	–	4, 6
3.5 Gundrilling	HSS	3		1, 86	–	–	4, 6
	Carbide	2		1, 86	–	–	4, 6
3.6 Pressure Coolant Reaming (Gun Reaming)	HSS	3		1, 4	–	–	5, 7
	Carbide	3		1, 4	–	–	4, 6
3.7 Reaming	HSS	3		0, 4	–	–	5, 7
	Carbide	3		0, 4	–	–	4, 6
3.9 Boring	HSS	3, 5		0, 4	–	–	3
	Carbide	2, 5		0	–	–	3
3.11 Boring	Diamond	–		–	–	–	–
3.12 Counterboring and Spotfacing	HSS	3, 5		0, 4	–	–	5, 7
	Carbide	2, 5		0, 4	–	–	4, 6
3.13 Trepanning	HSS	3		4, 86	–	–	3
	Carbide	2		1, 4	–	–	3
3.14 Honing	–	90		90	–	–	90
3.15 Burnishing	–	–		–	–	–	–
4.1 Tapping	HSS	3		1, 4	–	–	3

OPERATION	TOOL MATERIAL OR ABRASIVE	40. Refractory Metals, Wrought, Cast and P/M		41. Zinc Alloys, Cast	42. Lead Alloys, Cast	43. Tin Alloys, Cast	44. Uranium, Wrought
		170 to 320 Bhn	—	80 to 100 Bhn	10 to 20 Bhn (500 kg)	15 to 30 Bhn (500 kg)	56 to 58 R_A
5.1 Planing	HSS	—		—	—	—	—
	Carbide	—		—	—	—	—
5.2 Broaching	HSS	—		0, 1, 4	—	—	—
	Carbide	—		0, 1	—	—	—
6.1 Power Hack Sawing	HSS	3		1, 4	0*	0*	4, 6
6.2 Power Band Sawing	HSS	3		1, 4	0*	0*	4, 6
6.4 Circular Sawing	HSS	3		1, 4	0*	0*	5, 7
6.5 Circular Sawing	Carbide	3		0, 4	0*	0*	5, 7
6.6 Abrasive Cutoff	—	1, 83		0, 4	—	—	4, 6
7.1 Gear Hobbing	HSS	—		1, 4	—	—	—
7.2 Gear Cutting, Straight and Spiral Bevel	HSS	—		1, 4	—	—	—
7.3 Gear Shaping	HSS	—		1, 4	—	—	—
7.4 Gear Shaving	HSS	—		1, 4	—	—	—
7.5 Gear Grinding, Form	—	—		1, 4	—	—	—
8.1 Surface Grinding—Horiz. Spdl., Recip. Table	—	1, 83		4	—	—	4, 6
8.2 Surface Grinding—Horiz. Spdl., Recip. Table	CBN	—		—	—	—	—
8.3 Surface Grinding—Horiz. Spdl., Recip. Table	Diamond	—		—	—	—	—
8.4 Surface Grinding—Vertical Spdl., Rotary Table	—	1, 83		4	—	—	4, 6
8.5 Cylindrical Grinding	—	1, 83		4	—	—	4, 6
8.6 Cylindrical Grinding	CBN	—		—	—	—	—
8.7 Cylindrical Grinding	Diamond	—		—	—	—	—
8.8 Internal Grinding	—	1, 83		4	—	—	4, 6
8.9 Internal Grinding	CBN	—		—	—	—	—
8.10 Internal Grinding	Diamond	—		—	—	—	—
8.11 Centerless Grinding	—	1, 83		4	—	—	4, 6
8.13 Abrasive Belt Grinding	—	3, 91		—	—	—	—
8.14 Thread Grinding	—	1, 83		4	—	—	4, 6

*Compressed air may be used to facilitate chip removal.

16.2 Cutting Fluid Recommendations

OPERATION	TOOL MATERIAL OR ABRASIVE	45. Zirconium Alloys, Wrought		47. Powder Metal Alloys	48. Machinable Carbides		49. Carbides
		140 to 280 Bhn	—	All Hardness	40 to 51 R_C	68 to 70 R_C	89 to 94 R_A
1.1 Turning, Single Point and Box Tools	HSS	1, 4, 6		*	—	—	—
	Carbide	4, 6		*	—	—	—
1.3 Turning	Diamond	—		*	—	—	—
1.4 Turning, Cutoff and Form Tools	HSS	1, 5, 7		*	—	—	—
	Carbide	4, 6		*	—	—	—
1.5 Threading, Single Point	HSS	1, 5, 7		*	—	—	—
	Carbide	5, 7		*	—	—	—
1.6 Threading, Die	HSS	1, 5, 7		*	—	—	—
	Carbide	5, 7		*	—	—	—
1.7 Hollow Milling	HSS	1, 5, 7		*	—	—	—
	Carbide	4, 6		*	—	—	—
2.1 Face Milling	HSS	1, 4, 6		*	—	—	—
	Carbide	4, 6		*	—	—	—
2.2 Face Milling	Diamond	—		*	—	—	—
2.4 Slab Milling	HSS	1, 5, 7		*	—	—	—
	Carbide	4, 6		*	—	—	—
2.5 Side and Slot Milling—Arbor Mounted Cutters	HSS	1, 5, 7		*	—	—	—
	Carbide	4, 6		*	—	—	—
2.6 End Milling—Peripheral	HSS	1, 5, 7		*	—	—	—
	Carbide	4, 6		*	—	—	—
2.8 End Milling—Slotting	HSS	1, 5, 7		*	—	—	—
	Carbide	4, 6		*	—	—	—
2.9 Thread Milling	HSS	2, 5, 7		*	—	—	—
3.1 Drilling	HSS	1, 5, 7		*	—	—	—
	Carbide	4, 6		*	—	—	—
3.3 Oil-Hole or Pressurized-Coolant Drilling	HSS	1, 5, 7		*	—	—	—
	Carbide	4, 6		*	—	—	—
3.4 Spade Drilling	HSS	1, 5, 7		*	—	—	—
	Carbide	4, 6		*	—	—	—
3.5 Gundrilling	HSS	1, 5, 7		*	—	—	—
	Carbide	4, 6		*	—	—	—
3.6 Pressure Coolant Reaming (Gun Reaming)	HSS	1, 5, 7		*	—	—	—
	Carbide	4, 6		*	—	—	—
3.7 Reaming	HSS	1, 5, 7		*	—	—	—
	Carbide	4, 6		*	—	—	—
3.9 Boring	HSS	1, 5, 7		*	—	—	—
	Carbide	4, 6		*	—	—	—
3.11 Boring	Diamond	—		*	—	—	—
3.12 Counterboring and Spotfacing	HSS	1, 5, 7		*	—	—	—
	Carbide	4, 6		*	—	—	—
3.13 Trepanning	HSS	1, 5, 7		*	—	—	—
	Carbide	4, 6		*	—	—	—
3.14 Honing	—	90		*	80	80	80
3.15 Burnishing	—	—		*	—	—	—
4.1 Tapping	HSS	—		*	—	—	—

*Use the same cutting fluid as for cast alloys unless prohibited by part requirements for cleanliness and porosity.

OPERATION	TOOL MATERIAL OR ABRASIVE	45. Zirconium Alloys, Wrought		47. Powder Metal Alloys	48. Machinable Carbides		49. Carbides
		140 to 280 Bhn	—	All Hardness	40 to 51 R_C	68 to 70 R_C	89 to 94 R_A
5.1 Planing	HSS	—		*	—	—	—
	Carbide	—		*	—	—	—
5.2 Broaching	HSS	5, 7		*	—	—	—
	Carbide	4, 6		*	—	—	—
6.1 Power Hack Sawing	HSS	4, 6		*	0	—	—
6.2 Power Band Sawing	HSS	4, 6		*	0	—	—
6.4 Circular Sawing	HSS	5, 7		*	0	—	—
6.5 Circular Sawing	Carbide	4, 6		*	0	—	—
6.6 Abrasive Cutoff	—	4, 6		*	—	—	—
7.1 Gear Hobbing	HSS	2, 5, 7		*	—	—	—
7.2 Gear Cutting, Straight and Spiral Bevel	HSS	2, 5, 7		*	—	—	—
7.3 Gear Shaping	HSS	2, 5, 7		*	—	—	—
7.4 Gear Shaving	HSS	2, 5, 7		*	—	—	—
7.5 Gear Grinding, Form	—	2, 81		*	—	—	—
8.1 Surface Grinding—Horiz. Spdl., Recip. Table	—	2, 81		*	0, 4, 6	0, 4, 6	0, 4, 6
8.2 Surface Grinding—Horiz. Spdl., Recip. Table	CBN	—		*	—	—	—
8.3 Surface Grinding—Horiz. Spdl., Recip. Table	Diamond	—		*	—	4	4
8.4 Surface Grinding—Vertical Spdl., Rotary Table	—	2, 81		*	0, 4, 6	0, 4, 6	0, 4, 6
8.5 Cylindrical Grinding	—	2, 81		*	0, 4, 6	0, 4, 6	0, 4, 6
8.6 Cylindrical Grinding	CBN	—		*	—	—	—
8.7 Cylindrical Grinding	Diamond	—		*	—	4	4
8.8 Internal Grinding	—	2, 81		*	0, 4, 6	0, 4, 6	0, 4, 6
8.9 Internal Grinding	CBN	—		*	—	—	—
8.10 Internal Grinding	Diamond	—		*	—	4	4
8.11 Centerless Grinding	—	2, 81		*	0, 4, 6	0, 4, 6	0, 4, 6
8.13 Abrasive Belt Grinding	—	2, 3		*	0, 4, 6	0, 4, 6	0, 4, 6
8.14 Thread Grinding	—	2, 81		*	0, 4, 6	0, 4, 6	0, 4, 6

*Use the same cutting fluid as for cast alloys unless prohibited by part requirements for cleanliness and porosity.

16.2 Cutting Fluid Recommendations

OPERATION	TOOL MATERIAL OR ABRASIVE	50. Free Machining Magnetic Alloys		51. Magnetic Alloys		52. Free Machining Controlled Expansion Alloys	
		185 to 240 Bhn	–	185 to 240 Bhn	45 to 58 R_C	125 to 250 Bhn	–
1.1 Turning, Single Point and Box Tools	HSS	1, 5, 7		1, 5, 7	–	1, 5, 7	
	Carbide	–		–	–	–	
1.3 Turning	Diamond	–		–	–	–	
1.4 Turning, Cutoff and Form Tools	HSS	1, 5, 7		1, 5, 7	–	1, 5, 7	
	Carbide	2, 5, 7		2, 5, 7	–	2, 5, 7	
1.5 Threading, Single Point	HSS	–		–	–	–	
	Carbide	–		–	–	–	
1.6 Threading, Die	HSS	–		–	–	–	
	Carbide	–		–	–	–	
1.7 Hollow Milling	HSS	–		–	–	–	
	Carbide	–		–	–	–	
2.1 Face Milling	HSS	1, 5, 7		1, 5, 7	–	1, 5, 7	
	Carbide	–		–	–	–	
2.2 Face Milling	Diamond	–		–	–	–	
2.4 Slab Milling	HSS	1, 5, 7		1, 5, 7	–	1, 5, 7	
	Carbide	–		–	–	–	
2.5 Side and Slot Milling—Arbor Mounted Cutters	HSS	1, 5, 7		1, 5, 7	–	1, 5, 7	
	Carbide	–		2, 5, 7	–	–	
2.6 End Milling—Peripheral	HSS	1, 5, 7		1, 5, 7	–	1, 5, 7	
	Carbide	–		–	–	–	
2.8 End Milling—Slotting	HSS	1, 5, 7		1, 5, 7	–	1, 5, 7	
	Carbide	–		–	–	–	
2.9 Thread Milling	HSS	1, 5, 7		1, 5, 7	–	1, 5, 7	
3.1 Drilling	HSS	1, 5, 7		1, 5, 7	–	1, 5, 7	
	Carbide	–		–	–	–	
3.3 Oil-Hole or Pressurized-Coolant Drilling	HSS	1, 5, 7		1, 5, 7	–	1, 5, 7	
	Carbide	–		–	–	–	
3.4 Spade Drilling	HSS	1, 5, 7		1, 5, 7	–	–	
	Carbide	–		–	–	–	
3.5 Gundrilling	HSS	–		–	–	–	
	Carbide	–		–	–	–	
3.6 Pressure Coolant Reaming (Gun Reaming)	HSS	–		–	–	–	
	Carbide	–		–	–	–	
3.7 Reaming	HSS	1, 5, 7		1, 5, 7	–	1, 5, 7	
	Carbide	2, 5, 7		2, 5, 7	–	2, 5, 7	
3.9 Boring	HSS	1, 5, 7		1, 5, 7		1, 5, 7	
	Carbide	–		–	–	–	
3.11 Boring	Diamond	–		–	–	–	
3.12 Counterboring and Spotfacing	HSS	1, 5, 7		1, 5, 7	–	1, 5, 7	
	Carbide	–		2, 5, 7	–	–	
3.13 Trepanning	HSS	–		–	–	–	
	Carbide	–		–	–	–	
3.14 Honing	–	90		90	–	90	
3.15 Burnishing	–	–		–	–	–	
4.1 Tapping	HSS	2, 3		2, 3	–	2, 3	

OPERATION	TOOL MATERIAL OR ABRASIVE	50. Free Machining Magnetic Alloys		51. Magnetic Alloys		52. Free Machining Controlled Expansion Alloys	
		185 to 240 Bhn	—	185 to 240 Bhn	45 to 58 R_c	125 to 250 Bhn	—
5.1 Planing	HSS	—		—	—	—	
	Carbide	—		—	—	—	
5.2 Broaching	HSS	5, 7, 3		5, 7, 3	—	5 7, 3	
	Carbide	5, 7, 3		5, 7, 3	—	5, 7, 3	
6.1 Power Hack Sawing	HSS	5, 7, 3		5, 7, 3	—	5, 7, 3	
6.2 Power Band Sawing	HSS	5, 7, 3		5, 7, 3	—	5, 7, 3	
6.4 Circular Sawing	HSS	5, 7, 3		5, 7, 3	–	5, 7, 3	
6.5 Circular Sawing	Carbide	5, 7, 2		5, 7, 2	—	5, 7, 2	
6.6 Abrasive Cutoff	—	5, 7		5, 7	2, 3	5, 7	
7.1 Gear Hobbing	HSS	—		—	—	—	
7.2 Gear Cutting, Straight and Spiral Bevel	HSS	—		—	—	—	
7.3 Gear Shaping	HSS	—		—	—	—	
7.4 Gear Shaving	HSS	—		—	—	—	
7.5 Gear Grinding, Form	—	—		—	—	—	
8.1 Surface Grinding—Horiz. Spdl., Recip. Table	—	2, 3		2, 3	2, 3	2, 3	
8.2 Surface Grinding—Horiz. Spdl., Recip. Table	CBN	—		—	—	—	
8.3 Surface Grinding—Horiz. Spdl., Recip. Table	Diamond	—		—	—	—	
8.4 Surface Grinding—Vertical Spdl., Rotary Table	—	2, 3		2, 3	2, 3	2, 3	
8.5 Cylindrical Grinding	—	2, 3		2, 3	2, 3	2, 3	
8.6 Cylindrical Grinding	CBN	—		—	—	—	
8.7 Cylindrical Grinding	Diamond	—		—	—	—	
8.8 Internal Grinding	—	2, 3		2, 3	2, 3	2, 3	
8.9 Internal Grinding	CBN	—		—	—	—	
8.10 Internal Grinding	Diamond	—		—	—	—	
8.11 Centerless Grinding	—	2, 3		2, 3	2, 3	2, 3	
8.13 Abrasive Belt Grinding	—	3		3	3	3	
8.14 Thread Grinding	—	2, 3		2, 3	2, 3	2, 3	

16.2 Cutting Fluid Recommendations

OPERATION	TOOL MATERIAL OR ABRASIVE	53. Controlled Expansion Alloys		54. Carbons & Graphites		55. Glasses & Ceramics	
						Machinable Glass-Ceramic	Other
		125 to 250 Bhn	—	40 to 100 Shore	—	250 Knoop	Over 800 Knoop
1.1 Turning, Single Point and Box Tools	HSS	1, 5, 7		—		4, 93	—
	Carbide	—		—		4, 93	—
Turning	Diamond	—		—		4, 93	—
Turning, Cutoff and Form Tools	HSS	1, 5, 7		—		4, 93	—
	Carbide	—		—		4, 93	—
1.5 Threading, Single Point	HSS	—		—		4, 93	—
	Carbide	—		—		4, 93	—
1.6 Threading, Die	HSS	—		—		—	—
	Carbide	—		—		—	—
1.7 Hollow Milling	HSS	—		—		—	—
	Carbide	—		—		—	—
2.1 Face Milling	HSS	1, 5, 7		—		—	—
	Carbide	—		—		—	—
2.2 Face Milling	Diamond	—		—		4, 93	
2.4 Slab Milling	HSS	1, 5, 7		—		4, 93	-
	Carbide	—		—		—	—
2.5 Side and Slot Milling—Arbor Mounted Cutters	HSS	1, 5, 7		—		4, 93	—
	Carbide	—		—		4, 93	—
2.6 End Milling—Peripheral	HSS	1, 5, 7		—		4, 93	—
	Carbide	—		—		4, 93	—
2.8 End Milling—Slotting	HSS	1, 5, 7		—		4, 93	—
	Carbide	—		—		—	—
2.9 Thread Milling	HSS	1, 5, 7		—		4, 93	—
3.1 Drilling	HSS	1, 5, 7		—		4, 93	—
	Carbide	—		—		—	—
3.3 Oil-Hole or Pressurized-Coolant Drilling	HSS	1, 5, 7		—		4, 93	—
	Carbide	—		—		4, 93	—
3.4 Spade Drilling	HSS	—		—		4, 93	—
	Carbide	—		—		4, 93	—
3.5 Gundrilling	HSS	—		—		—	—
	Carbide	—		—		—	—
3.6 Pressure Coolant Reaming (Gun Reaming)	HSS	—		—		—	—
	Carbide	—		—		—	—
3.7 Reaming	HSS	1, 5, 7		—		—	—
	Carbide	2, 5, 7		—		—	—
3.9 Boring	HSS	1, 5, 7		—		4, 93	—
	Carbide	—		—		4, 93	—
3.11 Boring	Diamond	—		—		4, 93	—
3.12 Counterboring and Spotfacing	HSS	1, 5, 7		—		4, 93	—
	Carbide	—		—		4, 93	—
3.13 Trepanning	HSS	—		—		—	—
	Carbide	—		—		—	—
3.14 Honing	—	90		—		93	—
3.15 Burnishing	—	—		—		—	—
4.1 Tapping	HSS	2, 3		—		—	—

OPERATION	TOOL MATERIAL OR ABRASIVE	53. Controlled Expansion Alloys		54. Carbons & Graphites		55. Glasses & Ceramics	
						Machinable Glass-Ceramic	Other
		125 to 250 Bhn	—	40 to 100 Shore	—	250 Knoop	Over 800 Knoop
5.1 Planing	HSS	—		—		—	—
	Carbide	—		—		—	—
5.2 Broaching	HSS	5, 7, 3		0*		—	—
	Carbide	5, 7, 3		0*		—	—
6.1 Power Hack Sawing	HSS	5, 7, 3		0*		4, 93	—
6.2 Power Band Sawing	HSS	5, 7, 3		0*		4, 93	—
6.4 Circular Sawing	HSS	5, 7, 3		0*		4, 93	—
6.5 Circular Sawing	Carbide	5, 7, 2		0*		4, 93	—
6.6 Abrasive Cutoff	—	5, 7		0*		—	4, 93
7.1 Gear Hobbing	HSS	—		—		—	—
7.2 Gear Cutting, Straight and Spiral Bevel	HSS	—		—		—	—
7.3 Gear Shaping	HSS	—		—		—	—
7.4 Gear Shaving	HSS	—		—		—	—
7.5 Gear Grinding, Form	—	—		—		—	—
8.1 Surface Grinding—Horiz. Spdl., Recip. Table	—	2, 3		0*		4, 93	4, 93
8.2 Surface Grinding—Horiz. Spdl., Recip. Table	CBN	—		—		—	—
8.3 Surface Grinding—Horiz. Spdl., Recip. Table	Diamond	—		0*		4, 93	4, 93
8.4 Surface Grinding—Vertical Spdl., Rotary Table	—	2, 3		0*		4, 93	4, 93
8.5 Cylindrical Grinding	—	2, 3		0*		4, 93	4, 93
8.6 Cylindrical Grinding	CBN	—		—		—	—
8.7 Cylindrical Grinding	Diamond	—		0*		4, 93	4, 93
8.8 Internal Grinding	—	2, 3		0*		4, 93	4, 93
8.9 Internal Grinding	CBN	—		—		—	—
8.10 Internal Grinding	Diamond	—		0*		4, 93	4, 93
8.11 Centerless Grinding	—	2, 3		0*		4, 93	4, 93
8.13 Abrasive Belt Grinding	—	3		0*		4, 93	4, 93
8.14 Thread Grinding	—	2, 3		0*		4, 93	4, 93

*Compressed air may be used to aid swarf removal

16.2 Cutting Fluid Recommendations

OPERATION	TOOL MATERIAL OR ABRASIVE	56. Plastics	58. Flame (Thermal) Sprayed Materials			60. Precious Metals	61. Rubber
		–	–	–	–	–	–
1.1 Turning, Single Point and Box Tools	HSS	0, 4, 6		1		–	–
	Carbide	0, 4, 6		1		–	–
1.3 Turning	Diamond	0, 4, 6		–		–	–
1.4 Turning, Cutoff and Form Tools	HSS	0, 4, 6		–		–	–
	Carbide	0, 4, 6		–		–	–
1.5 Threading, Single Point	HSS	0, 4, 6		–		–	–
	Carbide	–		–		–	–
1.6 Threading, Die	HSS	0, 4, 6		–		–	–
	Carbide	–		–		–	–
1.7 Hollow Milling	HSS	0, 4, 6		–		–	–
	Carbide	–		–		–	–
2.1 Face Milling	HSS	0, 4, 6		–		–	–
	Carbide	0, 4, 6		–		–	–
2.2 Face Milling	Diamond	0, 4, 6		–		–	–
2.4 Slab Milling	HSS	0, 4, 6		–		–	–
	Carbide	0, 4, 6		–		–	–
2.5 Side and Slot Milling—Arbor Mounted Cutters	HSS	0, 4, 6		–		–	–
	Carbide	0, 4, 6		–		–	–
2.6 End Milling—Peripheral	HSS	0, 4, 6		–		–	–
	Carbide	0, 4, 6		–		–	–
2.8 End Milling—Slotting	HSS	0, 4, 6		–		–	–
	Carbide	0, 4, 6		–		–	–
2.9 Thread Milling	HSS	0, 4, 6		–		–	–
3.1 Drilling	HSS	0, 4, 6		–		–	–
	Carbide	0, 4, 6		–		–	–
3.3 Oil-Hole or Pressurized-Coolant Drilling	HSS	–		–		–	–
	Carbide	–		–		–	–
3.4 Spade Drilling	HSS	0, 4, 6		–		–	–
	Carbide	–		–		–	–
3.5 Gundrilling	HSS	–		–		–	–
	Carbide	–		–		–	–
3.6 Pressure Coolant Reaming (Gun Reaming)	HSS	–		–		–	–
	Carbide	–		–		–	–
3.7 Reaming	HSS	0, 4, 6		–		–	–
	Carbide	0, 4, 6		–		–	–
3.9 Boring	HSS	0, 4, 6		–		–	–
	Carbide	0, 4, 6		–		–	–
3.11 Boring	Diamond	0, 4, 6		–		–	–
3.12 Counterboring and Spotfacing	HSS	0, 4, 6		–		–	–
	Carbide	0, 4, 6		–		–	–
3.13 Trepanning	HSS	–		–		–	–
	Carbide	–		–		–	–
3.14 Honing	–	80		–		–	–
3.15 Burnishing	–	–		–		–	–
4.1 Tapping	HSS	0, 4, 6		–		–	–

OPERATION	TOOL MATERIAL OR ABRASIVE	56. Plastics	58. Flame (Thermal) Sprayed Materials			60. Precious Metals	61. Rubber
						Silver	
		–	–	–	–	–	–
5.1 Planing	HSS	–		–		–	–
	Carbide	–		–		–	–
5.2 Broaching	HSS	0, 1, 4, 6		–		–	–
	Carbide	0, 1, 4, 6		–		–	–
6.1 Power Hack Sawing	HSS	0, 1, 4, 6		–		4, 6	81
6.2 Power Band Sawing	HSS	0, 1, 4, 6		–		4, 6	81
6.4 Circular Sawing	HSS	0, 1, 4, 6		–		4, 6	81
6.5 Circular Sawing	Carbide	0, 1, 4, 6		–		4, 6	81
6.6 Abrasive Cutoff	–	0, 1, 4, 6		–		–	–
7.1 Gear Hobbing	HSS	0, 1, 4, 6		–		–	–
7.2 Gear Cutting, Straight and Spiral Bevel	HSS	0, 1, 4, 6		–		–	–
7.3 Gear Shaping	HSS	0, 1, 4, 6		–		–	–
7.4 Gear Shaving	HSS	0, 1, 4, 6		–		–	–
7.5 Gear Grinding, Form	–	0, 1, 4, 6		0, 4, 6		–	–
8.1 Surface Grinding—Horiz. Spdl., Recip. Table	–	0, 1, 4, 6		0, 4, 6		4, 6	4, 81
8.2 Surface Grinding—Horiz. Spdl., Recip. Table	CBN	–		–		–	–
8.3 Surface Grinding—Horiz. Spdl., Recip. Table	Diamond	–		–		–	0, 4, 81
8.4 Surface Grinding—Vertical Spdl., Rotary Table	–	0, 1, 4, 6		0, 4, 6		4, 6	4, 81
8.5 Cylindrical Grinding	–	0, 1, 4, 6		0, 4, 6		4, 6	4, 81
8.6 Cylindrical Grinding	CBN	–		–		–	–
8.7 Cylindrical Grinding	Diamond	–		–		–	0, 4, 81
8.8 Internal Grinding	–	0, 1, 4, 6		0, 4, 6		4, 6	4, 81
8.9 Internal Grinding	CBN	–		–		–	–
8.10 Internal Grinding	Diamond	–		–		–	0, 4, 81
8.11 Centerless Grinding	–	0, 1, 4, 6		0, 4, 6		4, 6	4, 81
8.13 Abrasive Belt Grinding	–	0, 1, 4, 6		0, 4, 6		4, 6	4, 81
8.14 Thread Grinding	–	0, 1, 4, 6		0, 4, 6		1	4, 81

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Cutting Fluid Key 16.3

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER
0	**DRY**	
1	**OILS—LIGHT DUTY (GENERAL PURPOSE)**	
	Straight Mineral Oil	
	Lafayette Blending Oil #1	American Oil & Supply Co.
	Amoco Neutral Oil. AMOLITE Oil No. 10 thru 68	Amoco Oil Co.
	Econ Oil 5. Econ Oil 10	Ashland Oil. Inc.
	Diamond Oils. Topaz Oils. Gascon Oils	Atlantic Richfield Co.
	Mineral Oil H-5	BP Oil. Inc.
	Bruko 1C. Bruko 2C. Bruko 3C. Bruko 4C	Bruce Products Corp.
	Chevron Utility Oil Grade 46	Chevron U.S.A. Inc.
	CITGO Amplex 22. CITGO Amplex 32. CITGO Amplex 46	Cities Service Co.
	Cook-Cut B-1. Cook-Cut B-5. Swiss-Cut 1816	Cook's Industrial Lubricants. Inc.
	CORAY. FAXAM	Exxon Co., U.S.A.
	BLENDING OIL 3333	Franklin Oil Corp. (Ohio)
	Gulf No. 372 Oil	Gulf Oil Corp.
	I.C. #1233. International Machine Oil #1	International Chemical Co.
	IRMCO 248. IRMCO 249	International Refining & Mfg. Co.
	Anza Oil	Lubrication Co. of America
	VANISHING OIL	Magnus Div., Economic Lab Inc.
	Kleer Kut Tri-Work	Pillsbury Chemical & Oil, Inc.
	Vehicle 6	Process Research Products
	#3 OIL. #6 OIL	G. Whitfield Richards Co.
	SYN-KUT 100. SYZ-KUT 300	Henry E Sanson & Sons. Inc.
	Space Age Blending Oil	Space Age Chemlube
	Spindel Oil No. 2 and 4	Specialty Products Co.
	Mineral Seal Oil. Factoil 39	Standard Oil Co. (Ohio)
	Starcut-37	Star Oil Company
	SUZICUT 113	Sun Petroleum Products Co.
	300 Oil 5. 522 Oil 19. Almag	Texaco Inc.
	NB BLENDING OIL	Tower Oil & Technology Co.
	W&B Cutting Oil 3016	The White & Bagley Co.
	Magnacut. Macco Blending Oil	Witco Chemical Corp.
	R-100 CUTTING OIL	Arthur C. Withrow Co.
	ZURN BLENDING OILS	O F Zurn Co.
	Straight Fatty Oil	
	Lafayette Lard Oil #2	American Oil & Supply Co.
	Brukut 11, Brukut 20	Bruce Products Corp.
	Cook-Cut A-11	Cook's Industrial Lubricants, Inc.
	W. S. LARD OIL	Franklin Oil Corp. (Ohio)
	I.C. #661-A. I.C #1259	International Chemical Co.
	IRMCO 040	International Refining & Mfg. Co.
	Modoc Lard Oil	Lubrication Co. of America
	DO-12	Magnus Div., Economics Lab Inc.
	Gipco Lard #1	Pillsbury Chemical & Oil, Inc.
	Special Prime Lard Oil	Reilly-Whiteman, Inc.
	CUTZOL F.O. 512	Rust-Lick, Inc.
	SYN-LARD	Henry E. Sanson & Sons, Inc.
	Tooiife 254	Specialty Products Co.

16.3 Cutting Fluid Key

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER
1	**OILS—LIGHT DUTY (GENERAL PURPOSE)** (Continued)	
	Straight Fatty Oil (Continued)	
	LARD OIL	Tower Oil & Technology Co
	W&B Lard Oil 1948	The White & Bagley Co.
	EWS LARD OIL (CODE 626)	Arthur C. Withrow Co.
	Mineral Oil + Fatty Oil	
	Lafayette SCF-20	American Oil & Supply Co.
	AMOCUT Oil No. 144-F	Amoco Oil Co.
	ARCO ML Oils	Atlantic Richfield Co.
	Bezora 22	BP Oil, Inc.
	Sparkut NF	Bruce Products Corp.
	Cook-Cut 25, Cook-Cut 30, Cook-Cut 1711	Cook's Industrial Lubricants, Inc
	FANOX N 33	Exxon Co., U.S.A.
	B-650 CUTTING OIL	Franklin Oil Corp (Ohio)
	Gulfcut 11A	Gulf Oil Corp.
	Habcool 344	H & B Petroleum Co.
	Cut-Max 110, Cut-Max 135	E. F. Houghton & Co.
	I.C. #152, I.C. #880	International Chemical Co
	IRMCO 240, IRMCO 242	International Refining & Mfg. Co.
	MINERAL LARD OIL	Keystone Div., Pennwalt Corp.
	LPS 1, LPS 2, LPS 3	LPS Research Laboratories, Inc.
	DO-5A, L-12	Magnus Div., Economics Lab Inc.
	Mobilmet 33, Mobilmet 34, Mobilmet 35	Mobil Oil Corp.
	Kleer Kut Dual Work	Pillsbury Chemical & Oil, Inc.
	Triple C 5500	Pro-Chem Inc.
	Non-Ferrous Aid	Process Research Products
	Petrolard 116, Petrolard 112	Reilly-Whiteman, Inc.
	NEAR-A-LARD OIL, SPECIAL NEAR-A-LARD OIL	G. Whitfield Richards Co.
	CUTZOL F O. 506, CUTZOL F O. 509	Rust-Lick, Inc.
	SYN-KUT 115, SYN-KUT 135	Henry E. Sanson & Sons, Inc.
	Space Age Blending Oil-Plus	Space Age Chemlube
	Toolife 250, Toolife 251, Toolife 256	Specialty Products Co.
	Factokut L-2	Standard Oil Co. (Ohio)
	Starcut-3950	Star Oil Company
	SUNICUT 150	Sun Petroleum Products Co.
	Extra Cutting Oil	Texaco Inc.
	TOWER E-533	Tower Oil & Technology Co.
	W&B Minolard Cutting Oil	The White & Bagley Co.
	Magnacut 40	Witco Chemical Corp.
	WITHROKUT 104 CUTTING OIL	Arthur C. Withrow Co.
	LARDOLEUM 5	O F Zurn Co.
	Mineral Oil + Additives	
	Lafayette B-16	American Oil & Supply Co.
	AMOCUT Tri-Purpose Cutting Oil	Amoco Oil Co
	Promax 1110	Ashland Oil, Inc.
	Clairo Oils	Atlantic Richfield Co.
	Sevora 37, Lumaro 25, Lumaro 36	BP Oil, Inc.
	Belco 1727 Cutting Oil	Bel-Ray Co., Inc.
	Brukut 177-X	Bruce Products Corp.

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER
1	**OILS—LIGHT DUTY (GENERAL PURPOSE)** (Continued)	
	Mineral Oil + Additives (Continued)	
	Chevron Metalworking Fluid 504	Chevron U.S.A Inc.
	Cook-Cut 70	Cook's Industrial Lubricants, Inc
	CURTIS 32-AS	Curtis Systems, Inc.
	EBONITE DUAL PURPOSE 702	Franklin Oil Corp. (Ohio)
	Cindepol 150, Cindepol 300	E F. Houghton & Co.
	I C. #852-A	International Chemical Co.
	IRMCO 200 Series	International Refining & Mfg. Co.
	121 Wax Cut	S. C. Johnson & Son, Inc.
	LPS 1, LPS 2, LPS 3	LPS Research Laboratories, Inc.
	Clear-Cut Ax	Lubrication Co. of America
	L-67, Magna-Draw 10	Magnus Div , Economics Lab Inc.
	Translube, Metkut 310	Metalloid Corp.
	Mobilmet 33, Mobilmet 34, Mobilmet 35, Mobilmet Omicron, Mobilmet Upsilon	Mobil Oil Corp.
	Magno Kut #11	Pillsbury Chemical & Oil, Inc.
	PC Lapping Oil, LE-2	Process Research Products
	NEAR-A-LARD #190-H OIL, #4-B OIL, #3-B OIL	G Whitfield Richards Co.
	CUTZOL 101-C	Rust-Lick, Inc.
	SYZ-KUT 216, SYZ-KUT 236	Henry E. Sanson & Sons Inc.
	Space Age Blending Oil-Plus	Space Age Chemlube
	Toolife VO	Specialty Products Co.
	Sulkleer 177X	Standard Oil Co. (Ohio)
	Starcut-3180	Star Oil Company
	SUNICUT 330	Sun Petroleum Products Co.
	Cleartex B	Texaco Inc.
	TOWERCUT F-901	Tower Oil & Technology Co.
	VSCC 5468	Van Straaten Chemical Co.
	W&B Cutting Oil 2169	The White & Bagley Co.
	WITHROKUT 102 CUTTING OIL	Arthur C. Withrow Company
	Mineral Oil + Sulfur and Chlorine Compounding	
	Lafayette B-115	American Oil & Supply Co.
	Promax 1220	Ashland Oil, Inc.
	Chevron Metalworking Fluid 502	Chevron U.S.A. Inc.
	CITGO Cutting Oil 400	Cities Service Co.
	Habcool 301a	H & B Petroleum Co.
	IRMCO 200 Series	International Refining & Mfg. Co.
	Magno Kut #1	Pillsbury Chemical & Oil, Inc.
	FRIGIDOL TRANSPARENT CUTTING OIL	G. Whitfield Richards Co.
	SYN-KUT 9-L	Henry E. Sanson & Sons, Inc.
	Space Age Blending Oil-Plus, Space Age T-61 Cutting Oil	Space Age Chemlube
	SUZICUT 350	Sun Petroleum Products Co.
	Dualtex	Texaco Inc.
	W&B Cutting Oil 2169	The White & Bagley Co.
	Macco Honing Oil, Macco Broach Oil 4-50, Epcut 31-BS-1, Maccut 16	Witco Chemical Corp.
	WITHROKUT 114 CUTTING OIL	Arthur C. Withrow Co.
	Mineral Oil + Fatty Oil + Additives	
	Promax 5352	Ashland Oil, Inc.
	Cook-Cut 70	Cook's Industrial Lubricants, Inc.

16.3 Cutting Fluid Key

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER
1	**OILS—LIGHT DUTY (GENERAL PURPOSE)** (Continued)	
	Mineral Oil + Fatty Oil + Additives (Continued)	
	DAUBERT MACRON M	Daubert Chemical Co.
	TF-460	Metalloid Corp
	CUTZOL 400-A	Rust-Lick, Inc.
	Dual Action Cutting Fluid #2	Tapmatic Corp.
2	**OILS—MEDIUM DUTY**	
	Sulfurized Mineral Oil	
	Lafayette B-16	American Oil & Supply Co.
	AMOCUT Oil No. 1195, AMOCUT Oil No. 159S	Amoco Oil Co.
	Promax 1004	Ashland Oil, Inc.
	Cutting Oil 70, Cutting Oil 100, Cutting Oil 160	Atlantic Richfield Co.
	Lumaro 24A	BP Oil, Inc.
	Brukut 4	Bruce Products Corp.
	PETROCHEM 709	Champions Choice, Inc.
	Cook-Cut 10, Cook-Cut 4985-Clear	Cook's Industrial Lubricants, Inc.
	DAUBERT GARIA S	Daubert Chemical Co.
	PEERLESS CUTTING OIL 3307	Franklin Oil Corp. (Ohio)
	IRMCO 269	International Refining & Mfg. Co.
	C-5, C-41, C-42, C-47	Lubrication Co. of America
	Fine Kut 41	Pillsbury Chemical & Oil, Inc.
	FRIGIDOL CUTTING OIL	G. Whitfield Richards Co.
	CUTZOL S.O 501	Rust-Lick, Inc.
	SYN-KUT 845	Henry E. Sanson & Sons Inc.
	Toolife 100	Specialty Products Co.
	Starcut-3719	Star Oil Company
	SUZICUT 300	Sun Petroleum Products Co.
	W&B Sulfurized Mineral Oil 3197	The White & Bagley Co.
	Compounded Sulfurized Mineral Oil	
	Lafayette B-16	American Oil & Supply Co.
	AMOCUT Oil No. 115FS, AMOCUT Oil No. 155FS	Amoco Oil Co.
	Promax 1220	Ashland Oil, Inc.
	Tulkut 160, Honol Oils	Atlantic Richfield Co.
	Lumaro 34A, Sevora 26A, Sevora 41A, Sevora 53A	BP Oil, Inc.
	Brukut 4LV, Brukut 102SR	Bruce Products Corp.
	PETROCHEM 703	Champions Choice, Inc.
	Chevron Metalworking Fluid 502	Chevron U.S.A. Inc.
	L 2051, L 2052	Chrysler Corp.
	DAUBERT GARIA C, DAUBERT GARIA H	Daubert Chemical Co.
	PEERLESS CUTTING OIL 967	Franklin Oil Corp. (Ohio)
	IRMCO 259	International Refining & Mfg. Co.
	RINCON 180	Lubrication Co. of America
	CUTTING COMPOUND No. 6	Magnus Div., Economics Lab Inc.
	Mobilmet 25, Mobilmet 26, Mobilmet 715, Mobilmet 735, Mobilmet Alpha, Mobilmet Sigma	Mobil Oil Corp.
	Fine Kut 41	Pillsbury Chemical & Oil, Inc.

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER
2	**OILS—MEDIUM DUTY** (Continued)	
	Compounded Sulfurized Mineral Oil (Continued)	
	FRIGIDOL L-6 CUTTING OIL	G. Whitfield Richards Co.
	SYZ-KUT 2023	Henry E. Sanson & Sons, Inc.
	Space Age Z-33 Cutting Oil	Space Age Chemlube
	Sulkleer 19E, Sulkleer 30, Sulkleer 102S, Sulkleer 163A	Standard Oil Co. (Ohio)
	Starcut-3531	Star Oil Company
	SUZICUT 400	Sun Petroleum Products Co.
	TREFOLEX Cutting Compound	Trefolex Industries, Inc.
	VSCC 5601	Van Straaten Chemical Co.
	W&B Cutting Oil 2151	The White & Bagley Co.
	B-5 CUTTING OIL	Arthur C. Withrow Co.
	Chlorinated Mineral Oil	
	Lafayette CP-6535	American Oil & Supply Co.
	AMOCUT Tri-Purpose Cutting Oil	Amoco Oil Co.
	TECTYL H-i40, PROMAX 1940	Ashland Oil, Inc.
	Chevron Metalworking Fluid 504	Chevron U.S.A. Inc.
	Cook-Cut 4938, Cook-Grind 4903	Cook's Industrial Lubricants, Inc.
	Cindol 3106	E. F. Houghton & Co.
	I.C #484-M, I.C. #484-MS	International Chemical Co.
	Hon-E-Kut 740-3	Lubrication Co. of America
	CUTTING COMPOUND No. 2, MAGNU DRAW 30	Magnus Div., Economics Lab Inc.
	Taplube, Translube, Multi-slide 21	Metalloid Corporation
	Spun Gold #1	Pillsbury Chemical & Oil, Inc.
	Rapid Tap	Relton Corp.
	LUBE-A-TUBE "EP" #6 COMPOUND, LUBE-A-TUBE "EP" #214-P COMPOUND	G. Whitfield Richards Co.
	CUTZOL 101-C, CUTZOL 711	Rust-Lick, Inc.
	CLARET-KUT 21	Henry E. Sanson & Sons, Inc.
	Space Age Z-34 Cutting Oil	Space Age Chemlube
	Toolife 703, Toolife 705	Specialty Products Co.
	Starcut-3260	Star Oil Company
	SUNICUT 201	Sun Petroleum Products Co.
	Dual Action Cutting Fluid #1	Tapmatic Corp.
	VSCC 5487-G	Van Straaten Chemical Co.
	W&B Cutting 2981	The White & Bagley Co.
	Sulfo-Chlorinated Mineral Oil	
	Lafayette A-13	American Oil & Supply Co.
	AMOCUT Oil 117 BCS	Amoco Oil Co.
	Promax 1401, Promax 1455	Ashland Oil, Inc.
	Brukut #7	Bruce Products Corp.
	PETROCHEM 704	Champions Choice, Inc.
	Chevron Metalworking Fluid 503	Chevron U.S.A. Inc.
	L 402, L 405, L 407	Chrysler Corp.
	MITEE Clear Thread Cutting Oil	DAP, Inc.
	I.C. #1280-A	International Chemical Co.
	IRMCO 220	International Refining & Mfg. Co.
	LCA Speed-Cut 105, 102, 104, 104B, 103	Lubrication Co. of America
	Flash Kut 101	Pillsbury Chemical & Oil, Inc.

16.3 Cutting Fluid Key

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER
2	**OILS—MEDIUM DUTY** (Continued)	
	Sulfo-Chlorinated Mineral Oil (Continued)	
	FRIGIDOL #401-T COMPOUND	G. Whitfield Richards Co.
	SYN-KUT 99-L	Henry E. Sanson & Sons, Inc.
	Space Age Z-35 Cutting Oil	Space Age Chemlube
	Starcut-3531	Star Oil Company
	SUNICUT 510	Sun Petroleum Products Co.
	W&B Cutting Oil 2151	The White & Bagley Co.
	"WADCO" Cutting and Threading Oil	J. C. Whitlam Manufacturing Co.
	Sulfurized Mineral Oil + Fatty Oil	
	Lafayette F-14	American Oil & Supply Co.
	AMOCUT Oil No. 155FS	Amoco Oil Co.
	Promax 1023	Ashland Oil, Inc.
	Autokut Oils	Atlantic Richfield Co.
	Sevora 26A, Sevora 41A, Sevora 53A	BP Oil, Inc.
	PETROCHEM 703	Champions Choice, Inc.
	Cook-Cut 15, Cook-Cut 40, Cook-Cut 1880	Cook's Industrial Lubricants, Inc.
	MITEE Dark Thread Cutting Oil	DAP, Inc.
	DAUBERT GARIA C, DAUBERT GARIA H	Daubert Chemical Co.
	PENNEX N 40	Exxon Co., U.S.A.
	PEERLESS 930	Franklin Oil Corp. (Ohio)
	Gulfcut 31A, Gulfcut 31C	Gulf Oil Corp.
	IRMCO 259	International Refining & Mfg. Co.
	Clear Cutting Oil C-47	Lubrication Co. of America
	Mobilmet 24, Mobilmet 25, Mobilmet 26, Mobilmet 37, Mobilmet 715, Mobilmet 735, Mobilmet Alpha, Mobilmet Sigma	Mobil Oil Corp.
	Flash Kut 101	Pillsbury Chemical & Oil, Inc.
	FRIGIDOL BASE "A" COMPOUND	G. Whitfield Richards Co.
	CUTZOL C.F.O. 507	Rust-Lick, Inc.
	SYZ-KUT 320	Henry E Sanson & Sons, Inc.
	Space Age Z-36 Cutting Oil	Space Age Chemlube
	Toolife 103	Specia.., Products Co.
	Sulkleer 30	Standard Oil Co. (Ohio)
	Starcut-3570	Star Oil Company
	SUNICUT 400	Sun Petroleum Products Co.
	W&B Cutting Oil 1749	The White & Bagley Co.
	WITHROKUT 132 CUTTING OIL	Arthur C. Withrow Co.
	Chlorinated Mineral Oil + Fatty Oil	
	Lumaro 36	BP Oil, Inc.
	L 415	Chrysler Corp.
	Cook-Cut 55, Swiss-Cut 51	Cook's Industrial Lubricants, Inc.
	CURTIS 64-AS	Curtis Systems, Inc.
	DAUBERT MACRON M	Daubert Chemical Co.
	PEERLESS 1211	Franklin Oil Corp. (Ohio)
	I.C. #152-S, I.C. #818	International Chemical Co.
	IRMCO 754	International Refining & Mfg. Co.
	Hon-E-Kut	Lubrication Co. of America
	EL CUT S	Magnus Div., Economics Lab Inc.
	Metkut #310, TF-308	Metalloid Corp.

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER

2 OILS—MEDIUM DUTY (Continued)

Chlorinated Mineral Oil + Fatty Oil (Continued)

Spun Gold #12	Pillsbury Chemical & Oil, Inc.
Petrosan EP43	Reilly-Whiteman, Inc.
NEAR-A-LARD #190-LV OIL, NEAR-A-LARD #13	G. Whitfield Richards Co.
CUTZOL C.F O. 509, CUTZOL LC, HONZOL 11-B	Rust-Lick, Inc.
SYN-KUT 3401, SYN-KUT M-2	Henry E. Sanson & Sons Inc.
Toolife 150, Toolife Swiss Screw Machine No. 3	Specialty Products Co.
Starcut-3360	Star Oil Company
W&B Cutting Oil 2871	The White & Bagley Co.
WITHROKUT 110 CUTTING OIL	Arthur C. Withrow Co.

Mineral Oil With Fatty Compounding + Sulfur and Chlorine Additives

Promax 5352, Promax 1310	Ashland Oil, Inc.
Cilora 19A, Lumaro 40A	BP Oil, Inc.
Brukut 9, Brukut 102, Brukut 102S, Bruko D-648	Bruce Products Corp.
Chevron Metalworking Fluid 503	Chevron U.S.A. Inc.
L 2045	Chrysler Corp.
CITGO Cutting Oil 425	Cities Service Co.
Cook's RTP Cutting Oil 4768	Cook's Industrial Lubricants, Inc
DAUBERT GARIA D	Daubert Chemical Co.
DORTAN N 14	Exxon Co., U.S.A.
Habcool 250	H & B Petroleum Co.
I.C. #634	International Chemical Co.
Mobilmet 715, Mobilmet 735	Mobil Oil Corp.
Triple C 53611	Pro-Chem Inc
PRP-9112	Process Research Products
FRIGIDOL #401-P COMPOUND	G. Whitfield Richards Co.
SYN-KUT 725, SYN-KUT 750	Henry E. Sanson & Sons Inc.
Space Age Z-37 Cutting Oil	Space Age Chemlube
Sulkleer 177X	Standard Oil Co. (Ohio)
SUNICUT 352	Sun Petroleum Products Co.
Transultex A, Transultex F	Texaco Inc.
TOWERCUT F-932	Tower Oil & Technology Co.
W&B Cutting Oil 2688	The White & Bagley Co.
WITHROKUT 136 CUTTING OIL	Arthur C. Withrow Co.
ZURNKUT 3 L X	O F Zurn Co.

Sulfo-Chlorinated Mineral Oil + Fatty Oil

Lafayette C-115	American Oil & Supply Co.
AMOCUT Oil 139 BCS	Amoco Oil Co.
Promax 1002	Ashland Oil, Inc.
Belco Cutting Oil 1735	Bel-Ray Co., Inc.
PETROCHEM 704	Champions Choice, Inc.
Chevron Metalworking Fluid 503	Chevron U.S.A. Inc.
Cook-Cut 4984-Dark, Cook-Cut 4889	Cook's Industrial Lubricants, Inc.
No. 80 Cutting Oil	DoALL Co.
DORTAN N 34	Exxon Co., U.S.A.
Gulfcut 41M	Gulf Oil Corp.
Cut-Max 206	E. F. Houghton & Co.
I.C. #283-C	International Chemical Co.

16.3 Cutting Fluid Key

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER
2	**OILS—MEDIUM DUTY** (Continued)	
	Sulfo-Chlorinated Mineral Oil + Fatty Oil (Continued)	
	IRMCO 268	International Refining & Mfg. Co.
	Flash Kut 11	Pillsbury Chemical & Oil, Inc.
	FRIGIDOL #401 COMPOUND	G. Whitfield Richards Co.
	SYZ-KUT 206, SYN-KUT 226, SYN-KUT 246	Henry E. Sanson & Sons Inc.
	Space Age Z-38 Cutting Oil	Space Age Chemlube
	Toolife 202	Specialty Products Co.
	Starcut-3531	Star Oil Company
	SUZICUT 500	Sun Petroleum Products Co.
	W&B Cutting Oil 2688	The White & Bagley Co.
	Maccut 11 Concentrate, Maccut 16 BGA, Maccut 1652 DO, Maccut 19 BG	Witco Chemical Corp.
	ZURN ULTRAKUT 70 S 1	O F Zurn Co.
	Compounded Sulfo-Chlorinated Mineral Oil + Fatty Oil	
	Lafayette C-75	American Oil & Supply Co.
	AMOCUT Oil 168 BC	Amoco Oil Co.
	Promax 1002	Ashland Oil, Inc.
	Transkut Oils	Atlantic Richfield Co.
	Cilora 39A, Cilora 59A	BP Oil, Inc.
	PETROCHEM 704	Champions Choice, Inc.
	Chevron Metalworking Fluid 503	Chevron U.S.A. Inc.
	Cook-Cut 20, Cook-Cut 1545	Cook's Industrial Lubricants, Inc.
	DAUBERT GARIA D	Daubert Chemical Co.
	Gulfcut 41D, Gulfcut 41E	Gulf Oil Corp.
	I.C. #1884-T	International Chemical Co.
	IRMCO 215	International Refining & Mfg. Co.
	LUBRICOOL 175	Larson Chemical Specialties
	Magno Base 201	Pillsbury Chemical & Oil, Inc.
	Gear Lap 2S	Process Research Products
	FRIGIDOL #401-PX COMPOUND	G. Whitfield Richards Co.
	BOOSTER-KUT 50	Henry E. Sanson & Sons, Inc.
	Space Age Z-39-Cutting Oil	Space Age Chemlube
	Starcut-3671	Star Oil Company
	SUNICUT 500	Sun Petroleum Products Co.
	TOWERCUT D-904	Tower Oil & Technology Co.
	VSCC 5299	Van Straaten Chemical Co.
	W&B Cutting Oil 2688	The White & Bagley Co.
	Maccut 1652 DO, Maccut 18-L	Witco Chemical Corp.
3	**OILS—HEAVY DUTY**	
	Sulfurized Mineral Oil	
	AMOCUT Oil No. 159S	Amoco Oil Co.
	PETROCHEM 709	Champions Choice, Inc.
	CITGO Cutting Oil 110	Cities Service Co.
	Cook-Cut 4985-Clear	Cook's Industrial Lubricants, Inc.
	PEERLESS 3307	Franklin Oil Corp. (Ohio)
	Smooth Cut 111, 112, 113, 114	Lubrication Co. of America

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER
3	**OILS—HEAVY DUTY** (Continued)	
	Sulfurized Mineral Oil (Continued)	
	Komp Kut 5493	Pillsbury Chemical and Oil Inc
	SYN-KUT 2023 AB	Henry E. Sanson & Sons Inc.
	Space Age 49-1-Cutting Oil	Space Age Chemlube
	Starcut-3068	Star Oil Company
	SUNICUT 300	Sun Petroleum Products Co
	W&B Sulfurized Mineral Oil 3197	The White & Bagley Co.
	Compounded Sulfurized Mineral Oil	
	AMOCUT Oil No. 189FS. AMOCUT Oil No. 155FS	Amoco Oil Co
	Promax 1130-S	Ashland Oil. Inc.
	Cilora 39A. Cilora 59A. Lumaro 40A. Sevora 53A	BP Oil. Inc.
	Belco Cutting Oil S-1191	Bel-Ray Co.. Inc.
	Bruko D-269	Bruce Products Corp.
	PETROCHEM 703	Champions Choice. Inc.
	CITGO Cutting Oil 120	Cities Service Co.
	Cook-Cut 4669. Cook-Cut 4770. Cook's Base 4876	Cook's Industrial Lubricants. Inc.
	DAUBERT GARIA D. DAUBERT GARIA G	Daubert Chemical Co
	PEERLESS 977. PEERLESS 967	Franklin Oil Corp. (Ohio)
	Mobilmet 27. Mobilmet 45. Mobilmet 814. Mobilmet 826. Mobilmet 833. Mobilmet Gamma. Mobilmet Omega	Mobil Oil Corp.
	Gipco "A"	Pillsbury Chemical and Oil. Inc.
	FRIGIDOL CUTTING OIL	G. Whitfield Richards Co.
	SYN-KUT BASE 55	Henry E. Sanson & Sons. Inc.
	Space Age 49-2 Cutting Oil	Space Age Chemlube
	Sulkleer 30. Sulkleer 102S	Standard Oil Co. (Ohio)
	Starcut-3068	Star Oil Company
	SUNICUT 415	Sun Petroleum Products Co.
	TOWER B-1136	Tower Oil and Technology Co.
	VSCC 5299	Van Straaten Chemical Co.
	W&B Cutting Oil 2555	The White & Bagley Co.
	Chlorinated Mineral Oil	
	Lafayette CP-6535	American Oil & Supply Co.
	Promax Q-1013	Ashland Oil. Inc.
	Bruko D-337	Bruce Products Corp.
	Cook's Base 1241. Cook's Base 4676	Cook's Industrial Lubricants. Inc.
	PEERLESS 1211. TAPPING COMPOUND 1715	Franklin Oil Corp. (Ohio)
	I.C. #871	International Chemical Co.
	122 Wax Cut	S. C. Johnson & Son. Inc.
	KOOLMIST FORMULA #88 TAP WAX	Kool Mist Corp.
	DO-91. DO-2A. MAGNU DRAW 40. MAGNU DRAW 50L. CHLOROLUBE 50H	Magnus Div.. Economics Lab Inc.
	Hon-E-Cut 740. 741. 742	Lubrication Co. of America
	Plastrol. Metdraw 407. Metdraw 446	Metalloid Corp.
	Spun Gold #3	Pillsbury Chemical and Oil. Inc.
	Die Gard 84	Reilly-Whiteman. Inc.
	LUBE-A-TUBE #81 COMPOUND	G. Whitfield Richards Co.
	CUTZOL 711	Rust-Lick. Inc.
	CLARET-KUT 35. CLARET-BASE	Henry E. Sanson & Sons. Inc.

16.3 Cutting Fluid Key

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER

3 OILS—HEAVY DUTY (Continued)

Chlorinated Mineral Oil (Continued)

Space Age 49-3 Cutting Oil	Space Age Chemlube
Toolife 720. Toolife 740. Toolife 770	Specialty Products Co
Starcut-3269	Star Oil Company
SUNICUT 201	Sun Petroleum Products Co.
TOWER A-1123	Tower Oil and Technology Co.
VSCC 5487-G	Van Straaten Chemical Co.
W&B Cutting Oil 2981	The White & Bagley Co.
WITHROBASE 434 CONCENTRATE	Arthur C. Withrow Co.

Sulfurized Mineral Oil + Sulfur, Chlorine, and Phosphorus Compounding

Bruko D-643	Bruce Products Corp.
Cook-Cut 4749. Cook-Grind 4806. Cook-Cut 4895. Cook's Base 4601	Cook's Industrial Lubricants. Inc.
IRMCO 793	International Refining & Mfg. Co.
VISTA*KUT Heavy Duty	Lubrication Co. of America
Triple C 5401	Pro-Chem Inc.
SYN-KUT FGO	Henry E. Sanson & Sons Inc
Toolife 203	Specialty Products Co.

Sulfo-Chlorinated Mineral Oil

Lafayette A-13	American Oil & Supply Co.
AMOCUT Oil No. 139 BCS. AMOCUT Oil No. 209 BCS	Amoco Oil Co.
Promax 1455-S	Ashland Oil. Inc.
PETROCHEM 707	Champions Choice. Inc.
Chevron Metalworking Fluid 503	Chevron U.S.A. Inc.
CITGO Cutting Oil 130	Cities Service Co.
Cook-Cut 4515	Cook's Industrial Lubricants. Inc.
I.C. #1226	International Chemical Co.
Thread Mate 101. 110. 202. 225	Lubrication Co. of America
Tapeze X-2. Thredwell	Metalloid Corp.
Black Velvet	Pillsbury Chemical and Oil. Inc.
FRIGIDOL TRANSPARENT CUTTING OIL. FRIGIDOL BASE "L" COMPOUND	G. Whitfield Richards Co.
CLARET-KUT 570. CLARET-KUT 27	Henry E. Sanson & Sons Inc.
SWEPCO 705 Heavy Duty Cutting Oil	Southwestern Petroleum Corp.
Space Age 49-4 Cutting Oil	Space Age Chemlube
Toolife 201	Specialty Products Co.
Starcut-3033	Star Oil Company
SUNICUT 510	Sun Petroleum Products Co.
TOWERCUT D-908	Tower Oil and Technology Co.
W&B Cutting Oil 2151	The White & Bagley Co.

Sulfurized Mineral Oil + Fatty Oil

AMOCUT Oil No. 189FS. AMOCUT Oil No. 155FS	Amoco Oil Co.
Promax 1023. Promax 1130-S. Promax 1160	Ashland Oil. Inc.
Autokut Oils	Atlantic Richfield Co.
Cook's Honing Oil 1995. Cook-Cut 1998. Cook-Cut 4950	Cook's Industrial Lubricants. Inc.
No. 120 Cutting Oil	DoALL Co.
PEERLESS 930	Franklin Oil Corp. (Ohio)
Gulfcut 31C	Gulf Oil Corp.

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER
3	**OILS—HEAVY DUTY** (Continued)	
	Sulfurized Mineral Oil + Fatty Oil (Continued)	
	IRMCO 266	International Refining & Mfg. Co
	KEYCUT 101	Keystone Division/Pennwalt Corp.
	Mobilmet 27, Mobilmet 29, Mobilmet 45, Mobilmet Gamma, Mobilmet Omega	Mobil Oil Corp.
	Spun Gold #14	Pillsbury Chemical and Oil, Inc.
	FRIGIDOL BASE "A" COMPOUND	G. Whitfield Richards Co.
	CUTZOL SFO-507	Rust-Lick, Inc.
	SYN-KUT 310	Henry E. Sanson & Sons, Inc.
	Space Age 49-5 Cutting Oil	Space Age Chemlube
	Toolife 102	Specialty Products Co.
	Sulkleer 30	Standard Oil Co. (Ohio)
	Starcut-3161	Star Oil Company
	SUNICUT 400	Sun Petroleum Products Co.
	W&B Cutting Oil 2555	The White & Bagley Co.
	WITHROBASE 424 CONCENTRATE	Arthur C. Withrow Co.
	Chlorinated Mineral Oil + Fatty Oil	
	TECTYL H-2, PROMAX 1002, TECTYL H-22, PROMAX 1022	Ashland Oil, Inc.
	Bruko D-591, Bruko D-579	Bruce Products Corp.
	Swiss-Cut 57, Swiss-Cut 71, Swiss Base 1956	Cook's Industrial Lubricants, Inc.
	CURTIS 55-CUT	Curtis Systems, Inc.
	No. 150 Cutting Oil	DoALL Co.
	Cut-Max 568	E. F. Houghton & Co.
	I.C. #484-EW, I.C. #845	International Chemical Co.
	IRMCO 754	International Refining & Mfg. Co.
	X-60	Metalloid Corp.
	Die Gard 89	Reilly-Whiteman, Inc.
	NEAR-A-LARD #20-A OIL	G. Whitfield Richards Co.
	CUTZOL LC, HONZOL 11-B	Rust-Lick, Inc.
	CLARET-KUT 10	Henry E. Sanson & Sons, Inc.
	SWEPCO 725 EXTRA Heavy Duty Cutting Oil	Southwestern Petroleum Corp.
	Space Age 49-6 Cutting Oil	Space Age Chemlube
	Toolife 254, Toolife Swiss Screw Machine No. 1, Toolife Swiss Screw Machine No. 2	Specialty Products Co.
	Starcut-3361	Star Oil Company
	TOWER A-1123	Tower Oil and Technology Co.
	W&B Cutting Oil 2872	The White & Bagley Co.
	WITHROBASE 436 CONCENTRATE	Arthur C. Withrow Co.
	Sulfo-Chlorinated Mineral Oil + Fatty Oil	
	Lafayette C-13	American Oil & Supply Co.
	AMOCUT Oil No. 139 BCS, AMOCUT Oil No. 209 BCS, AMOCUT Oil No. 309 BCS	Amoco Oil Co.
	Promax 1310	Ashland Oil, Inc.
	Cilora 39A	[illegible] Oil, Inc.
	Bruko D-621A	Bruce Products Corp.
	PETROCHEM THREAD KUT DARK	Champions Choice, Inc.
	Chevron Metalworking Fluid 503	Chevron U.S.A. Inc.
	CITGO Cutting Oil 140	Cities Service Co.
	Cook-Cut 1685, Cook-Cut 4949, Cook-Cut 4559	Cook's Industrial Lubricants, Inc.

16.3 Cutting Fluid Key

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER
3	**OILS—HEAVY DUTY** (Continued)	
	Sulfo-Chlorinated Mineral Oil + Fatty Oil (Continued)	
	No. 240 Cutting Oil	DoALL Co.
	DORTAN N 36	Exxon Co., U.S.A.
	Gulfcut 45A	Gulf Oil Corp.
	Cut-Max 236, Cut-Max Base 7	E. F. Houghton & Co.
	I.C. #283-C, I.C. #629, I.C. #1220-A	International Chemical Co.
	IRMCO 229	International Refining & Mfg. Co.
	Threadmate 110	Lubrication Co of America
	Black Velvet 77	Pillsbury Chemical and Oil, Inc.
	LUBE-A-TUBE "EP-MR" #6 OIL, FRIGIDOL #401-P COMPOUND	G. Whitfield Richards Co.
	SYN-KUT SPECIAL 725, SYN-KUT SPECIAL 750	Henry E. Sanson & Sons, Inc.
	Space Age 49-7 Cutting Oil	Space Age Chemlube
	Sulkleer 19E, Sulkleer 162S, Sulkleer 163A	Standard Oil Co. (Ohio)
	Starcut-3031	Star Oil Company
	SUZICUT 501	Sun Petroleum Products Co.
	TOWERCUT D-908	Tower Oil and Technology Co.
	VSCC 5495	Van Straaten Chemical Co.
	W&B Cutting Oil 2698	The White & Bagley Co.
	Maccut 11 Concentrate, Maccut 16 BGA, Maccut 1652 DO	Witco Chemical Corp.
	WITHROKUT 158 CUTTING OIL	Arthur C. Withrow Co.
	Compounded Sulfo-Chlorinated Mineral Oil + Fatty Oil	
	Lafayette B-16	American Oil & Supply Co.
	Promax 1022	Ashland Oil, Inc.
	Ordnance Oils	Atlantic Richfield Co.
	Belco 730-S Cutting Oil	Bel-Ray Co., Inc.
	Bruko D-647, Bruko D-637	Bruce Products Corp.
	PETROCHEM THREAD KUT DARK	Champions Choice, Inc.
	Chevron Metalworking Fluid 503	Chevron U.S.A. Inc.
	Cook-Cut 20, Cook-Cut 1545, Cook-Tap #1, Cook-Tap 1157	Cook's Industrial Lubricants, Inc.
	DAUBERT GARIA D, DAUBERT GARIA G	Daubert Chemical Co.
	PENNEX N 47	Exxon Co., U.S.A.
	Gulfcut 45B, Gulfcut 21D	Gulf Oil Corp.
	Habcool 318, Habcool 277	H & B Petroleum Co.
	I.C. #815-A, I.C. #1894	International Chemical Co.
	IRMCO 790	International Refining & Mfg. Co.
	M-60-3	S. C. Johnson & Son, Inc.
	Exzact 750	Lubrication Co. of America
	Black Velvet 25	Pillsbury Chemical and Oil, Inc.
	LUBE-A-TUBE "EP-M" COMPOUND, FRIGIDOL #401-A COMPOUND	G. Whitfield Richards Co.
	BOOSTER-KUT PLV	Henry E. Sanson & Sons, Inc.
	Space Age 49-8 Cutting Oil	Space Age Chemlube
	Toolife 205	Specialty Products Co.
	Starcut-3461	Star Oil Company
	SUNICUT 500	Sun Petroleum Products Co.
	TOWERCUT D-908	Tower Oil and Technology Co.
	VSCC 5510-R, VSCC 5700	Van Straaten Chemical Co.
	W&B Cutting Oil 2192	The White & Bagley Co.
	Maccut 1652 DO, Maccut 18-L	Witco Chemical Corp.
	WITHROKUT 203 CUTTING OIL	Arthur C. Withrow Co.

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER

3 OILS—HEAVY DUTY (Continued)

Sulfo-Chlorinated Fatty Oil

Promax H-333	Ashland Oil, Inc.
Cook's Compound 4710	Cook's Industrial Lubricants, Inc.
IRMCO 252	International Refining & Mfg. Co.
Elcoa Base 201	Lubrication Co. of America
Magno Base 41	Pillsbury Chemical and Oil, Inc
LUBE-A-TUBE "EP-M" COMPOUND	G. Whitfield Richards Co.
SYN-KUT 99	Henry E. Sanson & Sons Inc.
Space Age 49-9 Cutting Oil	Space Age Chemlube
Toolife 208	Specialty Products Co.
W&B Base 2844	The White & Bagley Co.

Sulfurized Fatty Oil

Promax H-3	Ashland Oil, Inc.
Cadrex #1, Safrex #1	Cook's Industrial Lubricants, Inc.
IRMCO 055	International Refining & Mfg. Co.
Nu-Mac 11	Lubrication Co. of America
CUTTING BASE 66	Magnus Div., Economics Lab Inc.
Gipco Base 11M	Pillsbury Chemical and Oil, Inc.
FRIGIDOL BASE "V" COMPOUND, FRIGIDOL BASE "VR" COMPOUND	G. Whitfield Richards Co.
CUTZOL SFO-507	Rust-Lick, Inc.
SYN-KUT 340	Henry E. Sanson & Sons Inc.
Toolife Base 17, Toolife 404	Specialty Products Co.
W&B Base L	The White & Bagley Co.
"RUGGED CUT" Cutting and Threading Oil	J. C. Whitlam Manufacturing Co.
WITHROBASE 423 CONCENTRATE	Arthur C. Withrow Co.

Mineral Oil + Added Fat, Sulfur, Chlorine, and Phosphorus Compounding

Cook's Base 4601, Cook-Cut 4749, Cook-Grind 4806	Cook's Industrial Lubricants, Inc.
Gulfcut 41H	Gulf Oil Corp.
I.C. #1885	International Chemical Co.
IRMCO 791	International Refining & Mfg. Co.
LUBRICOOL 280	Larson Chemical Specialties
Specialube H-104	Lubrication Technology, Inc.
Sintolin X-2	Process Research Products
SYN-KUT FGO	Henry E. Sanson & Sons Inc.
Sultex F	Texaco Inc.
ZURN ULTRAKUT 70 S	O F Zurn Co.

4 EMULSIFIABLE OILS—LIGHT DUTY (GENERAL PURPOSE)

Soluble Oil

Lafayette Soluble Oil #1	American Oil & Supply Co.
AMOCOOL Soluble Oil, Amocool Soluble Oil	Amoco Oil Co.
Adsol 1, Adsol 100	Ashland Oil, Inc.
Crystex Sol. Oil, Emulsicool Sol. Oil, RISO Sol. Oil, Sol Oil DO, Sol. Oil Z, Tooltex Sol. Oil, No. 1 Sol. Oil, 943 Sol. Oil	Atlantic Richfield Co.
Soluble Oil #371, Fedaro CM, Fedara GS, Fedaro HW, Fedaro SB	BP Oil, Inc.

16.3 Cutting Fluid Key

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER
4	**EMULSIFIABLE OILS—LIGHT DUTY (GENERAL PURPOSE)** (Continued)	
	Soluble Oil (Continued)	
	Barco Soluble Oil 15	Bel-Ray Co . Inc.
	Brusol A	Bruce Products Corp.
	PETROCHEM SOLUBLE OIL	Champions Choice. Inc.
	Chevron Soluble Oil	Chevron U.S.A. Inc.
	L 470. L 481. L 493. L 3022 HW. L 3033 NB	Chrysler Corp.
	CITGO Cutting Oil 205. CITGO Cutting Oil 210	Cities Service Co.
	Cook-Cool 500. Cook-Cool 1235	Cook's Industrial Lubricants. Inc.
	COOL SPEED 500. DAUBERT DROMUS B	Daubert Chemical Co.
	No. 470 Soluble Oil	DoALL Co.
	KUTWELL 30. KUTWELL 40	Exxon Co.. U.S.A.
	TOOL COOL 1854	Franklin Oil Corp. (Ohio)
	Fremont-7040. Fremont-7042. Fremont-7043. Fremont-7045	Fremont Industries, Inc.
	Gulfcut Soluble Oil	Gulf Oil Corp.
	Habcool 747	H & B Petroleum Co.
	A.S.O.	E. F. Houghton & Co.
	I.C. #1651. Tooleze #2000	International Chemical Co.
	KEYCUT SOLUBLE OIL	Keystone Division/Pennwalt Corp.
	301. 303. 304. 333. 309. 322 Soluble Oils	Lubrication Co. of America
	CLEAN CUT. MAGNA COOL CC. EL SOL R	Magnus Div./Economics Lab Inc.
	TRIM SOL LC	Master Chemical Corp.
	Metsol. Oxitrol Air-O-Mist	Metalloid Corp.
	Hamikut	Harry Miller Corp.
	Mobilmet S-123. Mobilmet S-127. Mobilmet 104	Mobil Oil Corp.
	Oakite Formula 59	Oakite Products. Inc.
	Cutlass C 5500	Pillsbury Chemical & Oil. Inc.
	Polar Sol 500	Polar Chip. Inc.
	Triple C 3000	Pro-Chem Inc.
	Rycosol 19. Cupromul 23	Reilly-Whiteman, Inc.
	LUBE-WELL D-100 SPECIAL SOLUBLE OIL. LUBE-WELL S-42 SOLUBLE OIL	G. Whitfield Richards Co.
	CUTZOL WS-10. CUTZOL WS-11	Rust-Lick, Inc.
	SYN-SOL D A. SYN-SOL 60. ANTISEPTIC SOLUBLE OIL	Henry E. Sanson & Sons Inc.
	Space Age T-61 Cutting Oil. Space Age Z-33 Cutting Oil. Space Age Z-34 Cutting Oil. Space Age Z-35 Cutting Oil. Space Age Z-36 Cutting Oil. Space Age Z-37 Cutting Oil. Space Age #78. Soluble Oil 20-1	Space Age Chemlube
	Toolife 301	Specialty Products Co.
	Staysol 4X. Staysol 77	Standard Oil Co. (Ohio)
	Starsol-2950	Star Oil Company
	SECO. SECO 11	Sun Petroleum Products Co.
	Soluble Oil D	Texaco Inc.
	TOWERSOL H-978	Tower Oil & Technology Co.
	VSCC 255-A. VSCC 653	Van Straaten Chemical Co.
	W&B RP Soluble Oil 1999	The White & Bagley Co.
	Macco 163, 230-JL-3, Grinding oil 445	Witco Chemical Corp.
	WITHROSOL 310 SOLUBLE OIL. WITHROSOL 315 SOLUBLE OIL	Arthur C. Withrow Co.
	ZURNSOL 19	O F Zurn Co.

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER
4	**EMULSIFIABLE OILS—LIGHT DUTY (GENERAL PURPOSE)** (Continued)	
	Semichemical	
	AMOCOOL Transparent Coolant	Amoco Oil Co.
	Brukool 127	Bruce Products Corp.
	COOL SPEED 515	Daubert Chemical Co.
	TOOL COOL AR SOLUBLE	Franklin Oil Corp. (Ohio)
	I.C. 124	International Chemical Co.
	IRMCO 302	International Refining & Mfg. Co.
	Hamikleer	Harry Miller Corp.
	CHOICE-CUT	Monroe Chemical Co. Inc.
	Hy Kut 9737	Pillsbury Chemical & Oil, Inc.
	Triple C 3020	Pro-Chem Inc.
	Sintolin OP2, HD	Process Research Products
	Rycosol 60 SDG	Reilly-Whiteman, Inc.
	GWR COMPOUND	G. Whitfield Richards Co.
	CUTZOL WS-5100	Rust-Lick, Inc.
	SYN-KUT 125-P	Henry E. Sanson & Sons, Inc.
	Ami-Lube X-15	Tron-X Research Corp.
	VSCC 938	Van Straaten Chemical Co.
	W&B Lubricant 1888	The White & Bagley Co.
	Macco 158-C, Macco Syncrocut 167-DM-9, New Solube-D	Witco Chemical Corp.
	Semisynthetic	
	Brukool 82-C, Brukool 121	Bruce Products Corp.
	12 D 192	Chrysler Corp.
	Cook-Coolex 40, Cook-Cool 1300, Cook-Cool 4893	Cook's Industrial Lubricants, Inc.
	COOL SPEED 363	Daubert Chemical Co.
	TOOL COOL 1369	Franklin Oil Corp. (Ohio)
	I.C. #343-S	International Chemical Co.
	J-Cool, Trampol-X, Coldstream	S. C. Johnson & Son, Inc.
	CLEAR-CUT C	Larson Chemical Specialties
	Heavy Duty 302 Carbo-Flo, Florosol	Lubrication Co. of America
	Hamikleer	Harry Miller Corp.
	CHOICE-CUT	Monroe Chemical Co. Inc.
	Hy Kut 105	Pillsbury Chemical & Oil, Inc.
	Triple C 2670	Pro-Chem Inc.
	Sintolin OP2, HD	Process Research Products
	LUBE-WELL "CD" COMPOUND	G. Whitfield Richards Co.
	CUTZOL WS-15, CUTZOL WS-30	Rust-Lick, Inc.
	SYZ-KUT H	Henry E. Sanson & Sons, Inc.
	Toolife 316	Specialty Products Co.
	SUNICOOL 6	Sun Petroleum Products Co.
	ME II Super Concentrate (Recirculating)	Tapmatic Corp.
	Ami-Lube X-20	Tron-X Research Corp.
	VSCC 537, VSCC 545-E	Van Straaten Chemical Co.
	W&B Concentrate 3100	The White & Bagley Co.
	Macco Syncrocut 980-W-1, Macco Syncrocut 980-MM-2	Witco Chemical Corp.

16.3 Cutting Fluid Key

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER
5	**EMULSIFIABLE OILS—HEAVY DUTY**	
	Sulfurized Fatty Soluble Oil	
	Lafayette Soluble Oil #60	American Oil & Supply Co.
	AMOCOOL HD Soluble Oil	Amoco Oil Co.
	PETROCHEM 100	Champions Choice, Inc.
	L 485 HW	Chrysler Corp.
	Soluble Cadrex 1838	Cook's Industrial Lubricants, Inc.
	KUTWELL EP 66	Exxon Co., U.S.A.
	TOOL COOL 1342	Franklin Oil Corp. (Ohio)
	Gulfcut Heavy Duty Soluble Oil	Gulf Oil Corp.
	All Purpose Base	E. F. Houghton & Co.
	I.C. #1648	International Chemical Co.
	IRMCO 340	International Refining & Mfg. Co.
	Hamikut	Harry Miller Corp.
	WHEELMATE 819	Norton Co.
	Foil Kut 5350	Pillsbury Chemical & Oil, Inc.
	Triple C 3002	Pro-Chem Inc.
	FRIGIDOL #222 COMPOUND, FRIGIDOL #222-T COMPOUND	G. Whitfield Richards Co.
	ANTISEPTIC ALL PURPOSE BASE	Henry E. Sanson & Sons, Inc.
	Toolife 303	Specialty Products Co.
	Solopex-2760	Star Oil Company
	TOWER G-941	Tower Oil & Technology Co.
	Macco Hi Sul 588-EM	Witco Chemical Corp.
	WITHROSOL 320 SOLUBLE OIL	Arthur C. Whitrow Co.
	Chlorinated Soluble Oil	
	Lafayette Soluble Oil #71	American Oil & Supply Co.
	AMOCOOL SS Fluid	Amoco Oil Co.
	Adsol 2	Ashland Oil, Inc.
	Trukut EP-C	Atlantic Richfield Co.
	12 U 49, L 485 HW	Chrysler Corp.
	CIMPERIAL 18, CIMPERIAL 1010, CIMPERIAL 1011	Cincinnati Milacron, Products Div.
	CITGO Cutting Oil 215, CITGO Cutting Oil 220	Cities Service Co.
	Cook-Cool 2020, Cook-Cool 4782, Cook-Cool 4718	Cook's Industrial Lubricants, Inc.
	CURTIS S-6, CURTIS S-7, CURTIS S-21, CURTIS S-DD-100	Curtis Systems, Inc.
	COOL SPEED 2010	Daubert Chemical Co.
	TOOL COOL 1385, TOOL COOL 1485	Franklin Oil Corp. (Ohio)
	Hocut 733, Hocut 747	E. F. Houghton & Co.
	I.C. #922	International Chemical Co.
	MAGNU DRAW 10, MAGNU DRAW 30, MAGNU DRAW 40, MAGNU DRAW 50L, CHLOROLUBE 50H	Magnus Div./Economics Lab Inc.
	TRIM SOL	Master Chemical Corp.
	Plastrol, Metsol WOS	Metalloid Corp.
	Hamikut	Harry Miller Corp.
	PRIME-CUT	Monroe Chemical Co., Inc.
	WHEELMATE 607	Norton Co.
	Sword Kut C5100	Pillsbury Chemical & Oil, Inc.
	Sintolin E-1	Process Research Products
	Rycosol 69	Reilly-Whiteman Inc.
	LUBE-WHEEL S-47-H SOLUBLE OIL, LUBE-WELL S-47 SOLUBLE OIL	G. Whitfield Richards Co.
	CUTZOL WS-10, CUTZOL WS-20, CUTZOL WS-5050	Rust-Lick, Inc.

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER
5	**EMULSIFIABLE OILS—HEAVY DUTY** (Continued)	
	Chlorinated Soluble Oil (Continued)	
	TOOLMATE. SYN-SOL 1000	Henry E. Sanson & Sons Inc.
	Space Age 49-3-Cutting Oil	Space Age Chemlube
	Toolife 315	Specialty Products Co.
	Staysol 743	Standard Oil Co. (Ohio)
	Starsol-2800	Star Oil Company
	EMULSUZ 51	Sun Petroleum Products Co.
	TOWERSOL G-966	Tower Oil & Technology Co.
	VSCC 710	Van Straaten Chemical Co.
	W&B HD Soluble Oil 2213	The White & Bagley Co.
	Macco 472, Macco 472-MPA, Macco 478, Macco 768 MTS-3	Witco Chemical Corp.
	WITHROSOL 323 SOLUBLE OIL	Arthur C. Whitrow Co.
	Sulfo-Chlorinated Fatty Soluble Oil	
	Lafayette Soluble Oil #71	American Oil & Supply Co.
	Adsol 3	Ashland Oil, Inc.
	Trukut EP-SC	Atlantic Richfield Co.
	Fedaro EPSC	BP Oil, Inc.
	Bel-Ray WS-6-HD	Bel-Ray Co., Inc.
	Brukool 100, Brusol C, Brukool 131	Bruce Products Corp.
	PETROCHEM 101	Champions Choice, Inc.
	CIMPERIAL 20	Cincinnati Milacron, Products Div.
	Cook-Cool 1400	Cook's Industrial Lubricants, Inc.
	DAUBERT DROMUS SD	Daubert Chemical Co.
	POWER-CUT No. 360	DoALL Co.
	TOOL COOL 1397	Franklin Oil Corp. (Ohio)
	Habcool 312	H & B Petroleum Co.
	Hocut 3210-X, Permasol HD-20	E. F. Houghton & Co.
	I.C. #939-NP	International Chemical Co.
	IRMCO 335	International Refining & Mfg. Co.
	LUBRI-FLO 1000, LUBRI-FLO 440	Larson Chemical Specialties
	EP COOLANT, MAGNA COOL EP, EL SOL-SC	Magnus Div./Economics Lab Inc.
	TRIM SOL S	Master Chemical Corp.
	Hamidraw	Harry Miller Corp.
	Mobilmet 140, Mobilmet 160	Mobil Oil Corp.
	MONROE HD	Monroe Chemical Co., Inc.
	WHEELMATE 810, WHEELMATE 811	Norton Co.
	Rapier Kut 5200	Pillsbury Chemical & Oil, Inc.
	Triple C 3011	Pro-Chem Inc.
	Sintolin E-100	Process Research Products
	LUBE-WELL S-43 SOLUBLE OIL	G. Whitfield Richards Co.
	CUTZOL PB-10	Rust-Lick, Inc.
	SYN-SOL 300	Henry E. Sanson & Sons, Inc.
	SWEPCO 720 Water Soluble Cutting Oil	Southwestern Petroleum Corp.
	Space Age 49-4-Cutting Oil	Space Age Chemlube
	Staysol EPSC	Standard Oil Co. (Ohio)
	Solopex-2770	Star Oil Company
	EMULSUN 54	Sun Petroleum Products Co.
	Soluble Oil HD, TEXGOLD	Texaco Inc.
	TOWERSOL G919	Tower Oil & Technology Co.

16.3 Cutting Fluid Key

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER
5	**EMULSIFIABLE OILS—HEAVY DUTY** (Continued)	
	Sulfo-Chlorinated Fatty Soluble Oil (Continued)	
	VSCC 700. VSCC 708	Van Straaten Chemical Co.
	Macco Extrudoil 51-DE. Spermasol EP. Kelcut 203-EP-Soluble	Witco Chemical Corp.
	WITHROSOL 322 SOLUBLE OIL	Arthur C. Whitrow Co.
	ZURNTURN 004	O F Zurn Co.
	Semichemical	
	AMOCOOL SS Fluid	Amoco Oil Co.
	Brukool 129	Bruce Products Corp.
	CIMPERIAL 15	Cincinnati Milacron. Products Div.
	COOL SPEED 515	Daubert Chemical Co.
	Libricoolant 930 Sol. Oil (Mineral with natural sulfur)	DuBois Chemicals
	I.C. #1667	International Chemical Co.
	IRMCO 302	International Refining & Mfg. Co.
	TRIM EP	Master Chemical Corp.
	Hamikleer	Harry Miller Corp.
	CHOICE-CUT	Monroe Chemical Co.. Inc.
	Hy Kut 9737	Pillsbury Chemical & Oil. Inc.
	POLAR SOL 510	Polar Chip. Inc.
	Triple C 3010	Pro-Chem Inc.
	LUBE-A-TUBE "XAM" COMPOUND	G. Whitfield Richards Co.
	CUTZOL WS-5100	Rust-Lick. Inc.
	SYN-SOL	Henry E. Sanson & Sons. Inc.
	Space Age "Will-Cut"	Space Age Chemlube
	Ami-Lube SX-15	Tron-X Research Corp.
	VSCC 707	Van Straaten Chemical Co.
	W&B EP Concentrate 2828	The White & Bagley Co.
	Syncrocut 167-DM-9. Macco 158-C	Witco Chemical Corp.
	ZURNSOL 253	O F Zurn Co.
	Semisynthetic	
	Brukool 66. Brukool 128	Bruce Products Corp.
	Cook-Coolex 40	Cook's Industrial Lubricants. Inc.
	COOL SPEED 363	Daubert Chemical Co.
	Fremont-7030. Fremont-7031. Fremont-7032. Fremont-7033. Fremont-7035. Fremont-7036	Fremont Industries. Inc.
	I.C. 321K	International Chemical Co.
	IRMCO 303	International Refining & Mfg. Co.
	Slipstream 54. Coldstream	S. C. Johnson & Son. Inc.
	Hon-E-Cool	Lubrication Co. of America
	Hamikleer	Harry Miller Corp.
	CHOICE-CUT	Monroe Chemical Co., Inc.
	Oakite Formula B-50	Oakite Products. Inc.
	Hy Kut 9734	Pillsbury Chemical & Oil. Inc.
	Triple C 2511	Pro-Chem Inc.
	GWR COMPOUND	G. Whitfield Richards Co.
	CUTZOL WS-15. CUTZOL WS-30	Rust-Lick. Inc.
	SYN-SOL DURO 55. P.O. CUTTING LIQUID	Henry E. Sanson & Sons Inc.
	Space Age "Will-Cut"	Space Age Chemlube
	Toolife 316	Specialty Products Co.

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER
5	**EMULSIFIABLE OILS—HEAVY DUTY** (Continued)	
	Semisynthetic (Continued)	
	ME II Super Concentrate (Recirculating)	Tapmatic Corp.
	Ami-Lube Regular	Tron-X Research Corp.
	VSCC 550-P	Van Straaten Chemical Co.
	W&B Concentrate 3100	The White & Bagley Co.
	Macco 980-W-1. Macco Syncrocut 980-MM-2	Witco Chemical Corp.
	ZURNSOL 254	O F Zurn Co.
6	**CHEMICAL AND SYNTHETICS—LIGHT DUTY (GENERAL PURPOSE)**	
	Solutions	
	CAMPBELLENE. CAMPBELLENE NO-NITRITE	Allison Campbell Div./Acco Industries
	Lafayette Soluble #91	American Oil & Supply Co.
	AMOCOOL Transparent Coolant	Amoco Oil Co.
	Adcool 1	Ashland Oil. Inc.
	Brukool 130. Brukool 77. Brukool 78	Bruce Products Corp.
	PETROCHEM CHEMICAL COOLANT	Champions Choice. Inc.
	L 1549. 12 D 192	Chrysler Corp.
	CIMFREE 104. CIMFREE 106. CIMFREE 108	Cincinnati Milacron. Products Div.
	Cook-Cool 1975 (Grinding). Cook-Cool 4988 (Grinding)	Cook's Industrial Lubricants. Inc.
	COOL SPEED 77-45. COOL SPEED 36	Daubert Chemical Co.
	Kleen-Kool	DoALL Co.
	Lubricoolant 925. Lubricoolant 926	DuBois Chemicals
	Fremont-5018	Fremont Industries. Inc.
	Houghto-Grind 60	E. F. Houghton & Co.
	I.C. 124	International Chemical Co.
	IRMCO 120. IRMCO 110	International Refining & Mfg. Co.
	50 Cool. TL-131. Millstream	S. C. Johnson & Son. Inc.
	KEYCUT 106	Keystone Division/Pennwalt Corp.
	KOOLMIST FORMULA #78 COOLANT	Kool Mist Corp.
	LPS 1. LPS 2. LPS 3	LPS Research Laboratories. Inc.
	BLUE COOLANT NF	Magnus Div./Economics Lab Inc.
	TRIM 9106. TRIM 9106CS. TRIM REGULAR. TRIM 7030. TRIM 5050. TRIM 2575. TRIM MIST. TRIM 9106WA	Master Chemical Corp.
	Metgrind #432. Metgrind #468	Metalloid Corp.
	Hamikleer	Harry Miller Corp.
	MONROE RI	Monroe Chemical Co.. Inc.
	WHEELMATE 464. WHEELMATE 467	Norton Co.
	Oakite Formula A. Oakite Formula C. Oakite Formula G	Oakite Products. Inc.
	Hone-Rite 306	Pillsbury Chemical & Oil. Inc.
	Polar Chip 347	Polar Chip. Inc.
	Sintolin R30. Aqualap 15C	Process Research Products
	Rycosol 66	Reilly-Whiteman. Inc.
	GWR #110	G. Whitfield Richards Co.
	RUST-LICK G-25-J. RUST-LICK G-25-AH. VYTRON	Rust-Lick. Inc.
	MIRROR-KOOL M-1. MIRROR-KOOL M-15	Henry E. Sanson & Sons. Inc.
	Kool-Aide I	Space Age Chemlube

16.3 Cutting Fluid Key

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER
6	**CHEMICAL AND SYNTHETICS—LIGHT DUTY (GENERAL PURPOSE)** (Continued)	
	Solutions (Continued)	
	Toolife 305	Specialty Products Co.
	Molecular Edge (Squirt on), ME II Super Concentrate (Recirculating)	Tapmatic Corp.
	TOWERKEM W-2110	Tower Oil & Technology Co.
	Ami-Lube Clear	Tron-X Research Corp.
	VSCC 990	Van Straaten Chemical Co.
	Bio-Cool 500	Westmont Industrial Products
	W&B Grinding Concentrate 1500	The White & Bagley Co.
	Syncrocut 980-CE-3, Syncrocut 850-A-3	Witco Chemical Corp.
	WITHROKOOL 334 CHEMICAL COOLANT	Arthur C. Withrow Co.
	ZURN KOOLKUT	O F Zurn Co.
	Synthetic Emulsions	
	Q-77 Coolant Concentrate	Associate Technical Sales Co.
	L 1542	Chrysler Corp.
	CIMCOOL S2	Cincinnati Milacron, Products Div.
	COOL SPEED 363	Daubert Chemical Co.
	KUTWELL 82	Exxon Co., U.S.A.
	Hocut 711	E. F. Houghton & Co.
	I.C. #922	International Chemical Co.
	Specialube 994	Lubrication Technology, Inc.
	Hamikleer	Harry Miller Corp.
	MONROE NN	Monroe Chemical Co., Inc.
	WHEELMATE 405, WHEELMATE 414, WHEELMATE 419, WHEELMATE 613	Norton Co.
	Hy Kut 105	Pillsbury Chemical & Oil, Inc.
	Polar Cut 400	Polar Chip, Inc.
	Triple C 2010	Pro-Chem Inc.
	Rycosol 77, Rycosol 87 NF	Reilly-Whiteman, Inc.
	LUBE-WELL D-171 SOLUBLE OIL	G. Whitfield Richards Co.
	CUTZOL WS-15	Rust-Lick, Inc.
	MIRROR-KOOL G-70	Henry E. Sanson & Sons, Inc.
	Kool-Aide XII	Space Age Chemlube
	Toolife 316	Specialty Products Co.
	SUNICOOL 6	Sun Petroleum Products Co.
	Ami-Lube Syn-12 Series	Tron-X Research Corp.
	W&B Lubricant 1888	The White & Bagley Co.
7	**CHEMICAL AND SYNTHETICS—HEAVY DUTY**	
	Solutions	
	CAMPBELLENE, CAMPBELLENE NO-NITRITE	Allison Campbell Div./Acco Industries
	Lafayette Synthetic #102	American Oil & Supply Co.
	Adcool 2	Ashland Oil, Inc.
	Brukool 106	Bruce Products Corp.
	PETROCHEM 130Z	Champions Choice, Inc.
	12 U 176, 12 U 182 B	Chrysler Corp.

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER
7	**CHEMICAL AND SYNTHETICS—HEAVY DUTY** (Continued)	
	Solutions (Continued)	
	CIMFREE 234, CIMFREE 238, CIMFREE 305, CIMFREE 307	Cincinnati Milacron, Products Div.
	Cook-Cool 1975 (Grinding), Cook-Cool 4988 (Grinding)	Cook's Industrial Lubricants, Inc.
	POWER-CUT HD-600	DoALL Co.
	TOOL COOL 268	Franklin Oil Corp. (Ohio)
	Fremont-7010, Fremont-7011	Fremont Industries, Inc.
	Gulfcut Soluble CB-2	Gulf Oil Corp.
	Hocut 702, Hocut 4206, Hydra-Cut 496	E. F. Houghton & Co.
	I.C. 2614	International Chemical Co.
	IRMCO 111	International Refining & Mfg. Co.
	KOOLMIST FORMULA #77 COOLANT	Kool Mist Corp.
	CLEAR-CUT 44	Larson Chemical Specialists
	Empactosol	Lubrication Co. of America
	Specialube 67D, Specialube 75	Lubrication Technology, Inc.
	TRIM HD, TRIM EP	Master Chemical Corp.
	Metchem #429, Metchem #474	Metalloid Corp.
	Hamikleer	Harry Miller Corp.
	WHEELMATE 658, WHEELMATE 689	Norton Co.
	Kool Kut X350	Pillsbury Chemical & Oil, Inc.
	POLAR CHIP 347L	Polar Chip, Inc.
	Sintolin ROD	Process Research Products
	GWR COMPOUND	G. Whitfield Richards Co.
	VYTRON, RUST-LICK G-52	Rust-Lick, Inc.
	E-COOL, MIRROR-KUT G-7	Henry E. Sanson & Sons Inc.
	Kool-Aide III	Space Age Chemlube
	Toolife 311	Specialty Products Co.
	Molecular Edge (Squirt on), ME II Super Concentrate (Recirculating)	Tapmatic Corp.
	TOWERKEM W-2110	Tower Oil & Technology Co.
	Ami-Lube 10X-Clear	Tron-X Research Corp.
	VSCC 951, VSCC 936	Van Straaten Chemical Co.
	Bio-Cool 700	Westmont Industrial Products
	W&B Concentrate 3100	The White & Bagley Co.
	Syncrocut 105, Syncrocut 172	Witco Chemical Corp.
	WITHROKOOL 340 CHEMICAL COOLANT	Arthur C. Withrow Co.
	ZURN ALL MET 6	O F Zurn Co.
	Synthetic Emulsions	
	Adcool 3	Ashland Oil, Inc.
	Brukool 132	Bruce Products Corp.
	12 U 41	Chrysler Corp.
	CIMCOOL FIVE STAR 40, CIMCOOL S4, CIMCOOL S8	Cincinnati Milacron, Products Div.
	COOL SPEED 363, COOL SPEED 515	Daubert Chemical Co.
	I.C. #922	International Chemical Co.
	Specialube 997A, Specialube 998	Lubrication Technology, Inc.
	Hamikleer	Harry Miller Corp.
	MONROE NN	Monroe Chemical Co., Inc.
	WHEELMATE 603, WHEELMATE 613, WHEELMATE 674	Norton Co.
	Hy Kut 9734	Pillsbury Chemical & Oil, Inc.
	POLAR EZE 444	Polar Chip, Inc.
	Triple C 2510	Pro-Chem Inc.

16.3 Cutting Fluid Key

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER
7	**CHEMICAL AND SYNTHETICS—HEAVY DUTY** (Continued)	
	Synthetic Emulsions (Continued)	
	Rycosol 99	Reilly-Whiteman, Inc.
	LUBE-WELL "X" COMPOUND	G. Whitfield Richards Co.
	CUTZOL WS-15	Rust-Lick, Inc.
	KING KOOL	Henry E. Sanson & Sons, Inc.
	Toolife 314	Specialty Products Co.
	Starsyn-5	Star Oil Company
	Ami-Lube Syn-12X Series	Tron-X Research Corp.
	VSCC 950, VSCC 938	Van Straaten Chemical Co.
	W&B Lubricant 2300	The White & Bagley Co.
	WITHROKOOL 339 CHEMICAL COOLANT	Arthur C. Withrow Co.
	ZURN KOOLKUT 252	O F Zurn Co.
8	**SPECIALS—LIGHT DUTY**	
	***80* Honing Oil—Light Duty**	
	Lafayette KM-16	American Oil & Supply Co.
	AMOCUT Oil No. 62FC	*Amoco Oil Co.*
	Econ 5, Promax 1074	Ashland Oil, Inc.
	Honol Oils	Atlantic Richfield Co.
	Bezora 3	BP Oil, Inc.
	Bruko D-666 (non-ferrous), Bruko D-667 (ferrous)	Bruce Products Corp.
	PETROCHEM HONING OIL	Champions Choice, Inc.
	CIMFREE 104, CIMFREE 200, CIMFREE 234, CIMFREE 238	Cincinnati Milacron, Products Div.
	Cook's 250 Compound	Cook's Industrial Lubricants, Inc.
	DAUBERT GARIA H	Daubert Chemical Co.
	MICROCOOL IC-9S: 90-10	Ex-Cell-O Tool & Abrasive Products
	MENTOR 28	Exxon Co., U.S.A.
	Gulfcut 11A, Gulfcut 11D	Gulf Oil Corp.
	I.C. #155-M	International Chemical Co.
	IRMCO 278, IRMCO 229	International Refining & Mfg. Co.
	LPS 1, LPS 2, LPS 3	LPS Research Laboratories, Inc.
	LUBRICOOL H/O	Larson Chemical Specialties
	Elcoa Honing Oil 213	Lubrication Co. of America
	L-12	Magnus Div./Economics Lab Inc.
	TRIM REGULAR, TRIM 7030, TRIM SOL LC	Master Chemical Corp.
	TF 382	Metalloid Corp.
	Hamilube	Harry Miller Corp.
	Alumicut	Mistic Metal Mover, Inc.
	Vacmul 3A	Mobil Oil Corp.
	Hone Rite 711	Pillsbury Chemical & Oil, Inc.
	GRA Honing Oil	Process Research Products
	Petrosan 102	Reilly-Whiteman, Inc.
	GWR HONING OIL	G. Whitfield Richards Co.
	HONZOL 11-B	Rust-Lick, Inc.
	SYN-HONE MM-LV	Henry E. Sanson & Sons Inc.

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER

8 SPECIALS—LIGHT DUTY (Continued)

80 Honing Oil—Light Duty (Continued)

Toolife Honing Oil	Specialty Products Co.
Factokut H	Standard Oil Co. (Ohio)
SUNICUT 102	Sun Petroleum Products Co.
MAN-845, CK-50 (for cast iron and aluminum only)	Sunnen Products Co.
Almag	Texaco Inc.
TOWER D-204	Tower Oil & Technology Co.
VSCC 5551-A	Van Straaten Chemical Co.
Bio-Hone 252	Westmont Industrial Products
W&B Honing Oil 2088	The White & Bagley Co.
Macco Honing Oil	Witco Chemical Corp.
WITHROKUT 104 CUTTING OIL	Arthur C. Withrow Co.

81 Chemical Grinding Fluids: Amine Nitrite Solution, Sodium Nitrite Solution, etc.

(NOTE: Products with * are Nitrite Free. See Chemical Fluids in section 16.1.)

Bel-Ray Coolant 12X	Bel-Ray Co., Inc.
Brukool 77, Brukool 106	Bruce Products Corp.
Cook-Cool 1975*, Cook-Cool 4988*	Cook's Industrial Lubricants, Inc.
COOL SPEED 77-45, COOL SPEED 363*, COOL SPEED 36*	Daubert Chemical Co.
DuBois 910 Synthetic (sodium nitride solution), DuBois 915	DuBois Chemicals
TOOL COOL 1392	Franklin Oil Corp. (Ohio)
Coolant Base 100	E. F. Houghton & Co.
I.C. #45, I.C. 124*	International Chemical Co.
Electrisol 308	Lubrication Co. of America
TRIM 9106*, TRIM REGULAR, TRIM 7030, TRIM 5050, TRIM 2575*, TRIM HD, TRIM EP, TRIM 9106WA*, TRIM CLEAR, TRIM HM, TRIM TI GRIND	
Metgrind #468*	Master Chemical Corp.
Immunol, Hamikleer	Metalloid Corp.
MONROE NN*, MONROE RI*	Harry Miller Corp.
WHEELMATE 203, WHEELMATE 205	Monroe Chemical Co., Inc.
Hone Rite 3795	Norton Co.
Polar Chip 347*, GRINDEX 11B	Pillsbury Chemical & Oil, Inc.
X55-30A	Polar Chip, Inc.
VYTRON, RUST-LICK B, RUST-LICK G-25-J, RUST-LICK G-25-AH*, RUST-LICK G-1066D	Reilly-Whiteman, Inc.
MIRROR-KOOL G-5, MIRROR-KUT G-7*	Rust-Lick, Inc.
Kool-Aide IV*	Henry E. Sanson & Sons, Inc.
Starsyn-5	Space Age Chemlube
VSCC 5551-A, Van Straaten 920*, Van Straaten 936*	Star Oil Company
W&B Grinding Coolant E-55	Van Straaten Chemical Co.
Syncrocut 172	The White & Bagley Co.
	Witco Chemical Corp.

82 Cutting Fluid for Aluminum

CAMPBELLENE NO-NITRITE	Allison Campbell Div./Acco Industies
Lafayette BM-112	American Oil & Supply Co.
AMOCUT Oil No. 62FC	Amoco Oil Co.
Promax 1074, Promax 1075	Ashland Oil, Inc.
ARCO ML Oils, Clairo Oils	Atlantic Richfield Co.

16.3 Cutting Fluid Key

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER
8	**SPECIALS—LIGHT DUTY** (Continued)	
	82 Cutting Fluid for Aluminum (Continued)	
	Fedora EPSC, Bezora 22	BP Oil, Inc.
	Brukool 127, Bruko D-680	Bruce Products Corp.
	PETROCHEM 709	Champions Choice, Inc.
	Chevron Metalworking Fluid 504, Chevron Soluble Oil	Chevron U.S.A. Inc.
	CIMCOOL AL, CIMCOOL S2, CIMCOOL S4, CIMCOOL S8, CIMFREE 234, CIMFREE 305, CIMPERIAL 15, CIMPERIAL 16, CIMPERIAL 1010, CIMPERIAL 1011	Cincinnati Milacron, Products Div.
	CITGO Cutting Oil 400	Cities Service Co.
	Cook-Cut 1711, Cook-Cut 30, Cook-Cool 1235 (Water soluble)	Cook's Industrial Lubricants, Inc.
	COOL SPEED 515	Daubert Chemical Co.
	No. 120 Cutting Oil, No. 470 Soluble Oil	DoALL Co.
	Freon T-B1, Freon HV-3	E. I. DuPont Co. Inc.
	Gulfcut 11D	Gulf Oil Corp.
	Habcool 202	H & B Petroleum Co.
	Cindol 3411, Cindol 3101, Cindol 3102, Cindol 3103	E. F. Houghton & Co.
	I.C. #1231-A, I.C. #131-A	International Chemical Co.
	IRMCO 249, IRMCO 242, IRMCO 278	International Refining & Mfg. Co.
	121 Wax Cut, Slipstream 54, Coldstream, J-Cool	S. C. Johnson & Son, Inc.
	LPS 1, LPS 2, LPS 3	LPS Research Laboratories, Inc.
	LUBRI-FLO 1000	Larson Chemical Specialties
	Vista-Kut	Lubrication Co. of America
	DO-5A	Magnus Div./Economics Lab Inc.
	TRIM SOL LC, TRIM SOL, TRIM 9106 WA, TRIM HD	Master Chemical Corp.
	WOS, Metsol, TF-306	Metalloid Corp.
	Hamikut	Harry Miller Corp.
	Alumicut (Al)	Mistic Metal Mover, Inc.
	PRIME-CUT	Monroe Chemical Co., Inc.
	WHEELMATE 607, WHEELMATE 674	Norton Co.
	Sword Kut C5100, Sabre Kut 5400	Pillsbury Chemical & Oil, Inc.
	Polar Cut 400	Polar Chip, Inc.
	Triple C 3010	Pro-Chem Inc.
	Sintolin E-1	Process Research Products
	Petrosan 116, Rycosol 19	Reilly-Whiteman, Inc.
	A-9 (A1)	Relton Corp.
	LUBE-WELL S-4A SOLUBLE OIL, LUBE-A-TUBE "XAM" COMPOUND	G. Whitfield Richards Co.
	CUTZOL WS-10, CUTZOL WS-11, CUTZOL WS-20, CUTZOL WS-5050, CUTZOL WS-500-A	Rust-Lick, Inc.
	SYN-KUT 105	Henry E. Sanson & Sons, Inc.
	Kool-Aide I, Kool-Aide IV, Kool-Aide XII	Space Age Chemlube
	Toolife 250, Toolife 304	Specialty Products Co.
	Factokut A-50-C, Factokut L-2, Staysol EPSC	Standard Oil Co. (Ohio)
	Starcut-3902	Star Oil Company
	TAP MAGIC ALUMINUM	Steco Corp.
	SUNICUT 150	Sun Petroleum Products Co.
	Molecular Edge (Squirt on), ME II Super Concentrate (Recirculating), Dual Action Cutting Fluid #2	Tapmatic Corp.
	Almag	Texaco Inc.
	TOWERCUT E-915	Tower Oil & Technology Co.
	Ami-Lube X-12 Series	Tron-X Research Corp.

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER
8	**SPECIALS—LIGHT DUTY** (Continued)	
	82 Cutting Fluid for Aluminum (Continued)	
	VSCC 45, VSCC 653	Van Straaten Chemical Co.
	Bio-Cool 700	Westmont Industrial Products
	W&B Cutting Oil 3016	The White & Bagley Co.
	ALUMTAP	Winfield Brooks Co., Inc.
	Macco 230-JL-3	Witco Chemical Corp.
	WITHROKUT 101 CUTTING OIL	Arthur C. Withrow Co.
	83 Cutting Fluid for Titanium—Light Duty	
	CAMPBELLENE. CAMPBELLENE NO-NITRITE	Allison Campbell Div./Acco Industries
	AMOCOOL Soluble Oil	Amoco Oil Co.
	Promax 1002	Ashland Oil, Inc.
	Crystex Sol. Oil, Emulsicool Sol. Oil, Sol. Oil DO, Sol. Oil Z, Tooltex Sol. Oil, No. 1 Sol. Oil, 943 Sol. Oil, Autokut Oils	Atlantic Richfield Co.
	Fedora EPSC	BP Oil, Inc.
	Brukool 4-37d	Bruce Products Corp.
	Chevron Metalworking Fluid 503	Chevron U.S.A. Inc.
	CIMFREE 234, CIMFREE 238, CIMCOOL S4, CIMCOOL FIVE STAR 40	Cincinnati Milacron, Products Div.
	Cook-Cool 1235, Cook-Coolex 40	Cook's Industrial Lubricants, Inc.
	COOL SPEED 515	Daubert Chemical Co.
	POWER-CUT HD-600	DoALL Co.
	Freon T-B1, Freon HV-3	E. I. DuPont Co. Inc.
	Hocut 711, Cindol 3212	E. F. Houghton & Co.
	I.C. #48, I.C. 124	International Chemical Co.
	IRMCO 278	International Refining & Mfg. Co.
	TL-131	S. C. Johnson & Son, Inc.
	LPS 1, LPS 2, LPS 3	LPS Research Laboratories. Inc.
	Threadmate 2254	Lubrication Co. of America
	TRIM TI GRIND, TRIM REGULAR, TRIM 7030, TRIM 9106WA, TRIM HD, TRIM SOL	Master Chemical Corp.
	Metkut #310	Metalloid Corp.
	Hamikut	Harry Miller Corp.
	Alumicut	Mistic Metal Mover, Inc.
	CHOICE-CUT, PRIME-CUT, MONROE HD	Monroe Chemical Co., Inc.
	WHEELMATE 602	Norton Co.
	Hone Rite TI-Cut	Pillsbury Chemical & Oil, Inc.
	Polar Chip 347	Polar Chip, Inc.
	Sintolin OP2	Process Research Products
	Rycosol 66	Reilly-Whiteman, Inc.
	GWR COMPOUND	G. Whitfield Richards Co.
	CUTZOL WS-500-A, VYTRON, CUTZOL 400-A	Rust-Lick, Inc.
	MIRROR-KUT G-7, SYN-SOL 300	Henry E. Sanson & Sons, Inc.
	Kool-Aide IV, Kool-Aide XII	Space Age Chemlube
	Staysol EPSC, Sulkleer 163A	Standard Oil Co. (Ohio)
	EMULSUN 31, EMULSUN 51	Sun Petroleum Products Co.
	Transultex D, Sultex D	Texaco Inc.
	Ami-Lube X-12 Series	Tron-X Research Corp.
	VSCC 550	Van Straaten Chemical Co.
	W&B Cutting Oil 2151	The White & Bagley Co.

16.3 Cutting Fluid Key

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER
8	**SPECIALS—LIGHT DUTY** (Continued)	
	83 Cutting Fluid for Titanium—Light Duty (Continued)	
	Bio-Cool 500	Westmont Industrial Products
	Macco 478	Witco Chemical Corp.
	WITHROKUT 210 CUTTING OIL	Arthur C. Withrow Co.
	84 Compressed Gas, Freon, Liquid CO_2	
	Freon T-B1, Freon HV-3	E. I. DuPont Co. Inc
	85 Grinding Fluid for Ferrous Metals	
	CAMPBELLENE, CAMPBELLENE NO-NITRITE	Allison-Campbell Div./Acco Industries
	Promax 1310	Ashland Oil, Inc.
	RISO Soluble Oil	Atlantic Richfield Co.
	PETROCHEM 108	Champions Choice, Inc.
	Chevron Soluble Oil	Chevron U.S.A. Inc.
	CIMFREE 104, CIMFREE 234, CIMFREE 238, CIMFREE 305, CIMFREE S4, CIMCOOL S8, CIMCOOL FIVE STAR 40, CIMPERIAL 1010, CIMPERIAL 1011, CIMPERIAL 18, CIMPERIAL 20	Cincinnati Milacron, Products Div.
	Cook-Cool 1975, Cook-Cool 4988	Cook's Industrial Lubricants, Inc.
	COOL SPEED 36, COOL SPEED 77-45	Daubert Chemical Co.
	Kleen-Kool, No. 470 Soluble Oil	DoALL Co.
	Fremont-5018M, Fremont-5019X, Fremont-7013	Fremont Industries, Inc.
	I.C. #1676	International Chemical Co.
	IRMCO 120	International Refining & Mfg. Co.
	Millstream, TL-131	S. C. Johnson & Son, Inc.
	LCA Trans Sol 303	Lubrication Co. of America
	Specialube 67D	Lubrication Technology, Inc.
	MAGNA COOL CC, CLEAN CUT, EL SOL R, BLUE COOLANT NF	Magnus Div./Economics Lab Inc.
	TRIM REGULAR, TRIM 7030, TRIM 9106, TRIM 9106WA, TRIM SOL, TRIM SOL S, TRIM CE, TRIM HD, TRIM EP, TRIM 5050, TRIM 9106CS, TRIM HM, TRIM CLEAR	Master Chemical Corp.
	Metsol	Metalloid Corp.
	Hamikleer, Hamigrind	Harry Miller Corp.
	PRIME-CUT, CHOICE-CUT, MONROE HD, MONROE RI	Monroe Chemical Co., Inc.
	Kool Grind 9054	Pillsbury Chemical & Oil, Inc.
	Polar Chip 347	Polar Chip, Inc.
	Gear Lap RIG-12	Process Research Products
	Rycosol 66	Reilly-Whiteman, Inc.
	SEMI-FLUID VASTOLEIN COMPOUND, GRIND-WELL #110 GRINDING COMPOUND	G. Whitfield Richards Co.
	RUST-LICK G-25-J, RUST-LICK G-25-AH, VYTRON, RUST-LICK G-1066D, CUTZOL WS-15	Rust-Lick, Inc.
	POWER'D OIL FOR GRINDING	Henry E. Sanson & Sons Inc.
	Kool-Aide I, Kool-Aide IV, Kool-Aide XII	Space Age Chemlube
	Toolife 100, Toolife 102, Toolife 103	Specialty Products Co.
	Factocool 65	Standard Oil Co. (Ohio)
	Star S.M. 3732	Star Oil Company
	SECO 14, 3% EMULSION	Sun Petroleum Products Co.
	Ami-Lube Regular	Tron-X Research Corp.
	W&B Grinding Coolant E-55, W&B Grinding Concentrate 1500	The White & Bagley Co.

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER
8	**SPECIALS—LIGHT DUTY** (Continued)	
85	**Grinding Fluid for Ferrous Metals** (Continued)	
	Bio-Cool 500S	Westmont Industrial Products
	Syncrocut 980-W-1	Witco Chemical Corp.
	WITHROKUT 117 CUTTING OIL	Arthur C. Withrow Co.
86	**Cutting Fluids for Gun Drilling and Trepanning**	
	AMOCUT Gundrill Oil	Amoco Oil Co.
	Promax 5352, Promax 1002, Promax 1074, Promax 1455-S	Ashland Oil, Inc.
	Ordnance Oils	Atlantic Richfield Co.
	Cilora 19A	BP Oil, Inc.
	Brusol A, Bruko D-666	Bruce Products Corp.
	PETROCHEM 710	Champions Choice, Inc.
	Chevron Metalworking Fluid 503	Chevron U.S.A. Inc.
	CIMFREE 305, CIMPERIAL 1010, CIMPERIAL 1011, CIMPERIAL 20	Cincinnati Milacron, Products Div.
	Cook-Cut 1940	Cook's Industrial Lubricants, Inc.
	DAUBERT GARIA H, DAUBERT GARIA T	Daubert Chemical Co.
	Gulfcut 44A, Gulfcut 45A	Gulf Oil Corp.
	I.C. #814-A	International Chemical Co.
	IRMCO 229	International Refining & Mfg. Co.
	LUBRI-FLO 1000	Larson Chemical Specialties
	Threadmate Gun Drilling Oil 5110	Lubrication Co. of America
	TRIM SOL S, TRIM EP, TRIM HD, TRIM SOL	Master Chemical Corp.
	Metkut #310	Metalloid Corp.
	Hamikut	Harry Miller Corp.
	Mobilmet 25, Mobilmet Alpha	Mobil Oil Corp.
	PRIME-CUT, CHOICE-CUT, MONROE HD	Monroe Chemical Co., Inc.
	Thio Glo 162	Pillsbury Chemical & Oil, Inc.
	Polar Chip 347	Polar Chip, Inc.
	Triple C 5201	Pro-Chem Inc.
	FRIGIDOL L-6 CUTTING OIL, NEAR-A-LARD #20-A	G. Whitfield Richards Co.
	CUTZOL SCFO-504	Rust-Lick, Inc.
	SYN-KUT GUN DRILLING OIL C	Henry E. Sanson & Sons Inc.
	Kool-Aide IV	Space Age Chemlube
	Toolife 202, Toolife 203	Specialty Products Co.
	Factocool 65	Standard Oil Co. (Ohio)
	Starcut-3075	Star Oil Company
	SUNICUT 425	Sun Petroleum Products Co.
	Transultex A, Transultex F	Texaco Inc.
	TOWERCUT F-932, TOWERCUT B-825	Tower Oil & Technology Co.
	Super Ami-Lube	Tron-X Research Corp.
	VSCC 5468	Van Straaten Chemical Co.
	W&B Cutting Oil 2190	The White & Bagley Co.
	Bio-Cool 500	Westmont Industrial Products
	Macco GD 100-12	Witco Chemical Corp.
	WITHROKUT 125 CUTTING OIL	Arthur C. Withrow Co.
	ZURNKUT 3 L X	O F Zurn Co.

16.3 Cutting Fluid Key

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER
8	**SPECIALS—LIGHT DUTY** (Continued)	
87	**Cutting Fluids for Copper**	
	Lafayette Soluble Oil #70, Lafayette SCF-20	American Oil & Supply Co.
	AMOCUT Oil No. 106BC, AMOCUT Oil 62FC, AMOCOOL SS Fluid	Amoco Oil Co.
	Promax 1074, Promax 1075, Promax 1710	Ashland Oil, Inc.
	ARCO ML Oils, Clairo Oils	Atlantic Richfield Co.
	Bezora 22, Fedora EPSC	BP Oil, Inc.
	Belco 1727 Cutting Oil	Bel-Ray Co., Inc.
	PETROCHEM 712	Champions Choice, Inc.
	Chevron Utility Oil Grade 46, Chevron Metalworking Fluid 504, Chevron Soluble Oil	Chevron U.S.A. Inc.
	CIMCOOL AL, CIMCOOL S2, CIMCOOL S4, CIMPERIAL 16, CIMPERIAL 1010, CIMPERIAL 1011	Cincinnati Milacron, Products Div.
	Cook-Cut 30, Cook-Cut 25, Cook-Cool 1235 (Water Soluble)	Cook's Industrial Lubricants, Inc.
	COOL SPEED 500, DAUBERT MACRON M	Daubert Chemical Co.
	No. 120 Cutting Oil, No. 150 Cutting Oil, No. 470 Soluble Oil	DoALL Co.
	Gulfcut 44A, Gulfcut 45A	Gulf Oil Corp.
	I.C. #1440-M, I.C. #1873, Tooleze #2000	International Chemical Co.
	IRMCO 242, IRMCO 282	International Refining & Mfg. Co.
	J-Cool, Trampol-X	S. C. Johnson & Son, Inc.
	MINERAL LARD OIL	Keystone Division/Pennwalt Corp.
	LUBRI-FLO 1000	Larson Chemical Specialties
	Elcoa Copper Cutting Oil 204N	Lubrication Co. of America
	MAGNA COOL CC, CLEAN CUT, CUTTING COMPOUND 6	Magnus Div./Economics Lab Inc.
	TRIM SOL, TRIM CE, TRIM 9106, TRIM 9106CS, TRIM 9106WA	Master Chemical Corp.
	Alumicut	Mistic Metal Mover, Inc.
	Mobilmet 306	Mobil Oil Corp.
	PRIME-CUT	Monroe Chemical Co., Inc.
	Sword Kut C5100	Pillsbury Chemical & Oil, Inc.
	Polar Chip 347 BBC	Polar Chip, Inc.
	Triple C 5000	Pro-Chem Inc.
	Sintolin E-1	Process Research Products
	Petrosan 116, Cupromul 23	Reilly-Whiteman, Inc.
	LUBE-WELL S-42-M SOLUBLE OIL, LUBE-WELL S-60-T SOLUBLE OIL, PERFECTED LUBE-WELL "AA" COMPOUND	G. Whitfield Richards Co.
	CUTZOL WS-11	Rust-Lick, Inc.
	MIRROR-KUT G-7, SYN-KUT 125	Henry E. Sanson & Sons, Inc.
	Kool-Aide IV, Kool-Aide XII	Space Age Chemlube
	Toolife 251, Toolife 304	Specialty Products Co.
	Factokut A-50-C, Factokut L-2, Staysol EPSC	Standard Oil Co. (Ohio)
	Starcut-3902	Star Oil Company
	TAP MAGIC ALUMINUM	Steco Corp.
	SUNICUT 201	Sun Petroleum Products Co.
	Cleartex B, Soluble Oil D	Texaco Inc.
	TOWER E-933	Tower Oil & Technology Co.
	Ami-Lube BR	Tron-X Research Corp.
	VSCC 545, VSCC 653	Van Straaten Chemical Co.
	W&B Minolard Cutting Oil	The White & Bagley Co.
	Bio-Cool 500	Westmont Industrial Products
	ALUMTAP	Winfield Brooks Co., Inc.
	Macco 768-1	Witco Chemical Corp.

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER

8 SPECIALS—LIGHT DUTY (Continued)

87 Cutting Fluids for Copper (Continued)

WITHROKUT 103 CUTTING OIL	Arthur C. Withrow Co.
ZURNSOL 254	O F Zurn Co.

88 Cutting Fluids for Magnesium

(PRECAUTION: Consult with cutting fluid supplier or manufacturer to be sure fluids do not contain water or other chemicals which may support combustion of magnesium.)

Lafayette BM-112	American Oil & Supply Co.
AMOCUT Oil 62FC	Amoco Oil Co.
Econ Oil 5	Ashland Oil, Inc.
ARCO ML Oils, Clairo Oils	Atlantic Richfield Co.
TAP 99	Beechem Laboratories
Mineral Oil H-5	BP Oil, Inc.
PETROCHEM THREAD KUT LIGHT	Champions Choice, Inc.
Chevron Metalworking Fluid 504	Chevron U.S.A. Inc.
CITGO Cutting Oil 400	Cities Service Co.
Cook-Cut B-5, Cook-Cut 1711	Cook's Industrial Lubricants, Inc.
No. 150 Cutting Oil	DoALL Co.
Gulfcut 11D	Gulf Oil Corp.
I.C. #1880	International Chemical Co.
IRMCO 249, IRMCO 242, IRMCO 282	International Refining & Mfg. Co.
KOOLMIST TAP SUPREME	Kool Mist Corp.
Elcomag 215	Lubrication Co. of America
DO-5A	Magnus Div./Economics Lab Inc.
Alumicut	Mistic Metal Mover, Inc.
Kleensol 792	Pillsbury Chemical & Oil. Inc.
Petrosan 112	Reilly-Whiteman, Inc.
A-9	Relton Corp.
NEAR-A-LARD OIL, #3-B OIL	G. Whitfield Richards Co.
SYN-KUT 105	Henry E. Sanson & Sons, Inc.
Kool-Aide IV, Kool-Aide XII	Space Age Chemlube
Toolife 250	Specialty Products Co.
Mineral Seal Oil	Standard Oil Co. (Ohio)
TAP MAGIC ALUMINUM	Steco Corp.
SUNICUT 102	Sun Petroleum Products Co.
Almag	Texaco Inc.
TOWERCUT E-915	Tower Oil & Technology Co.
Ami-Lube NC	Tron-X Research Corp.
W&B Cutting Oil 3016, W&B Minolard Cutting Oil	The White & Bagley Co.
ALUMTAP	Winfield Brooks Co., Inc.
Macco Magnacut	Witco Chemical Corp.
LARDOLEUM	O F Zurn Co.

89 Tapping Fluids, Compounds and Pastes

Adsol 3, Promax H-10	Ashland Oil, Inc.
CIMTAP, CIMTAP II	Cincinnati Milacron, Products Div.
Cook-Tap #1, Cook-Tap #2, Cook-Tap #3	Cook's Industrial Lubricants, Inc.
Tapping Cream	DoALL Co.
Habcool 344	H & B Petroleum Co.

16.3 Cutting Fluid Key

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER
8	**SPECIALS—LIGHT DUTY** (Continued)	
89	**Tapping Fluids, Compounds and Pastes** (Continued)	
	TRIM TAP LIGHT, TRIM TAP HEAVY	Master Chemical Corp.
	Taps-All, Taplube	Metalloid Corp.
	Alumicut	Mistic Metal Mover, Inc.
	COOL-TOOL	Monroe Chemical Co., Inc.
	TAPZOL, CUTZOL WS-20	Rust-Lick, Inc.
	THREADMATE	Henry E. Sanson & Sons, Inc.
	Space Age #20 Tapping Lube	Space Age Chemlube
	TAP MAGIC	The Steco Corp.
	Cutting Compound, Dual Action Cutting Fluid #1, Dual Action Cutting Fluid #2	Tapmatic Corp.
	TREFOLEX Cutting Compound	Trefolex Industries, Inc.
	W&B Cutting Oil 2192	The White & Bagley Co.
	TAPFREE	Winfield Brooks Co., Inc.
9	**SPECIALS—HEAVY DUTY**	
90	**Honing Oil—Heavy Duty**	
	AMOCUT Gundrill Oil	Amoco Oil Co.
	Promax 1130	Ashland Oil, Inc.
	Honol Oils	Atlantic Richfield Co.
	Bezora 3	BP Oil, Inc.
	Bruko D-666 (non-ferrous), Bruko D-667 (ferrous)	Bruce Products Corp.
	PETROCHEM 708	Champions Choice, Inc.
	Cook's Honing Oil 1995	Cook's Industrial Lubricants, Inc.
	DAUBERT GARIA T	Daubert Chemical Co.
	MICROCOOL IC-9 HONING OIL (Concentrate), MICROCOOL IC-9S: 80-20	Ex-Cell-O Tool & Abrasive Products
	I.C. #155	International Chemical Co.
	IRMCO 229	International Refining & Mfg. Co.
	LPS 1, LPS 2, LPS 3	LPS Research Laboratories, Inc.
	Threadmate Honing Oil 228	Lubrication Co. of America
	TRIM SOL S, TRIM EP, TRIM HD	Master Chemical Corp.
	Metcool 222, Metcool 999	Metalloid Corp.
	Vacmul 3D, Vacmul 21C	Mobil Oil Corp.
	United Base	Pillsbury Chemical & Oil, Inc.
	PRP 9112 Honing Additive	Process Research Products
	Petrosan EP43	Reilly-Whiteman, Inc.
	FRIGIDOL HONING OIL	G. Whitfield Richards Co.
	HONZOL 411-B	Rust-Lick, Inc.
	SYN-HONE MM	Henry E. Sanson & Sons, Inc.
	Factokut H	Standard Oil Co. (Ohio)
	Star-3701	Star Oil Company
	MAN-852 (Sulfur Free), MB-30	Sunnen Products Co.
	Transultex A	Texaco Inc.
	TOWER D-204	Tower Oil & Technology Co.
	VSCC 5299-A	Van Straaten Chemical Co.
	W&B Honing Oil 2088	The White & Bagley Co.
	Bio-Hone 253	Westmont Industrial Products
	Macco Honing Oil	Witco Chemical Corp.

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER

9 SPECIALS—HEAVY DUTY (Continued)

91 Cutting Fluids for Titanium—Heavy Duty

CAMPBELLENE, CAMPBELLENE NO-NITRITE	Allison Campbell Div./Acco Industries
AMOCOOL HD Soluble Oil	Amoco Oil Co.
Promax 1022	Ashland Oil, Inc.
Autokut Oils	Atlantic Richfield Co.
Brukool 4-37d	Bruce Products Corp.
CIMFREE 305, CIMPERIAL 1010, CIMPERIAL 1011, CIMPERIAL 20	Cincinnati Milacron, Products Div.
Cook-Coolex 40, Cook-Cool 2020, Cook-Cool 1400	Cook's Industrial Lubricants, Inc.
POWER-CUT HD-600, No. 470 Soluble Oil	DoALL Co.
Freon T-B1, Freon HV-3	E. I. DuPont Co. Inc.
I.C. #48-SDW, I.C. 124	International Chemical Co.
IRMVO 282	International Refining & Mfg. Co.
TL-131	S. C. Johnson & Son, Inc.
LPS 1, LPS 2, LPS 3	LPS Research Laboratories, Inc.
Empact 51	Lubrication Co. of America
TRIM HD, TRIM SOL, TRIM REGULAR	Master Chemical Corp.
X-60	Metalloid Corp.
MONROE HD, PRIME-CUT, CHOICE-CUT	Monroe Chemical Co., Inc.
Rapier Kut 5200	Pillsbury Chemical & Oil, Inc.
Polar Chip 347	Polar Chip, Inc.
Rycosol 69	Reilly-Whiteman, Inc.
FRIGIDOL L-6 CUTTING OIL	G. Whitfield Richards Co.
CUTZOL 400-A, CUTZOL WS-500-A, VYTRON	Rust-Lick, Inc.
MIRROR-KUT G-7-M, BOOSTER KUT PLV, SYN-SOL 600	Henry E. Sanson & Sons Inc.
SUNICUT 520	Sun Petroleum Products Co.
Transultex D, Sultex D	Texaco Inc.
Ami-Lube Super NC	Tron-X Research Corp.
VSCC 708	Van Straaten Chemical Co.
Bio-Cool 500	Westmont Industrial Products
W&B HD Soluble Oil 2945	The White & Bagley Co.
Macco 478	Witco Chemical Corp.
ZURNAGENT BD	O F Zurn Co.

92 Biodegradable Soluble Oil

Adsol 3	Ashland Oil, Inc.
Brukool 82-c, Bruko D-680	Bruce Products Corp.
Cook-Cool 4639D	Cook's Industrial Lubricants, Inc.
IRMCO 303	International Refining & Mfg. Co.
Kool Kut X350	Pillsbury Chemical & Oil, Inc.
Triple C 2100	Pro-Chem Inc.
Rycosol 11	Reilly-Whiteman, Inc.
LUBE-WELL "CD"	G. Whitfield Richards Co.
SYN-SOL 50, MIRROR-KUT G-7	Henry E. Sanson & Sons Inc.
ME II Super Concentrate (Recirculating)	Tapmatic Corp.
Bio Ami-Lube	Tron-X Research Corp.
VSCC 938	Van Straaten Chemical Co.
ZURNAGENT BD	O F Zurn Co.

16.3 Cutting Fluid Key

CODE NO.	TYPE AND TRADE NAME	MANUFACTURER
9	**SPECIALS—HEAVY DUTY** (Continued)	
93	**Ceramic and Glass Soluble Oil**	
	Soluble Oil #371	BP Oil, Inc.
	PETROCHEM 101	Champions Choice, Inc.
	CIMCOOL S2, CIMCOOL S4, CIMFREE 234, CIMFREE 238	Cincinnati Milacron, Products Div.
	Cook-Coolex 40	Cook's Industrial Lubricants, Inc.
	Hocut 219, Hocut 702, Hocut 714	E. F. Houghton & Co.
	I.C. #993-G	International Chemical Co.
	IRMCO 189	International Refining & Mfg. Co.
	130 Wax Cool, Slipstream 54	S. C. Johnson & Son, Inc.
	Ceramasol 3031	Lubrication Co. of America
	PRIME-CUT	Monroe Chemical Co., Inc.
	Hy Kut 6638	Pillsbury Chemical & Oil, Inc.
	Solap 30, MON-60	Process Research Products
	Rycosol 77	Reilly-Whiteman, Inc.
	LUBE-WELL "CD"	G. Whitfield Richards Co.
	CUTZOL WS-20, CUTZOL WS-15	Rust-Lick, Inc.
	SYN-GRIND 60-P	Henry E. Sanson & Sons, Inc.
	Kool-Aide XII	Space Age Chemlube
	Glassgrind Oil	Standard Oil Co. (Ohio)
	VSCC S-212	Van Straaten Chemical Co.
	W&B Lubricant 1888	The White & Bagley Co.
	Grind Rite 174	Witco Chemical Corp.
94	**Tapping Fluids, Compounds and Pastes**	
	Promax H-7, Promax Q-1013, Promax H-333	Ashland Oil, Inc.
	CIMTAP, CIMTAP II	Cincinnati Milacron, Products Div.
	Cook-Tap #1, Cook-Tap #2, Cook-Tap #3	Cook's Industrial Lubricants, Inc.
	CURTIS DD-50, CURTIS DD-80, CURTIS DD-100, CURTIS DD-200, CURTIS SDD-100 (emulsifiable)	Curtis Systems, Inc.
	Tapping Compound	DoALL Co.
	TAPPING COMPOUND 1715	Franklin Oil Corp. (Ohio)
	Habcool 318	H & B Petroleum Co.
	Tapeze #1271 (Paste)	International Chemical Co.
	KOOL MIST FORMULA #88 TAP WAX	Kool Mist Corp.
	TRIM TAP LIGHT, TRIM TAP HEAVY	Master Chemical Corp.
	Tapeze X-2	Metalloid Corp.
	Alumicut	Mistic Metal Mover, Inc.
	COOL-TOOL	Monroe Chemical Co., Inc.
	Rapid Tap, A-9 (for aluminum)	Relton Corp.
	TAPZOL, VYTRON TAPPING COMPOUND	Rust-Lick, Inc.
	TOOLMATE TAP	Henry E. Sanson & Sons, Inc.
	Space Age #23 Tapping Lube	Space Age Chemlube
	Startap-3202	Star Oil Company
	Cutting Compound, Dual Action Cutting Fluid #1, Dual Action Cutting Fluid #2	Tapmatic Corp.
	TREFOLEX Cutting Compound	Trefolex Industries, Inc.
	W&B Base 2844	The White & Bagley Co.
	MOLY-DEE TAPPING FLUID	Arthur C. Withrow Co.

SECTION 17

POWER AND FORCE REQUIREMENTS IN MACHINING

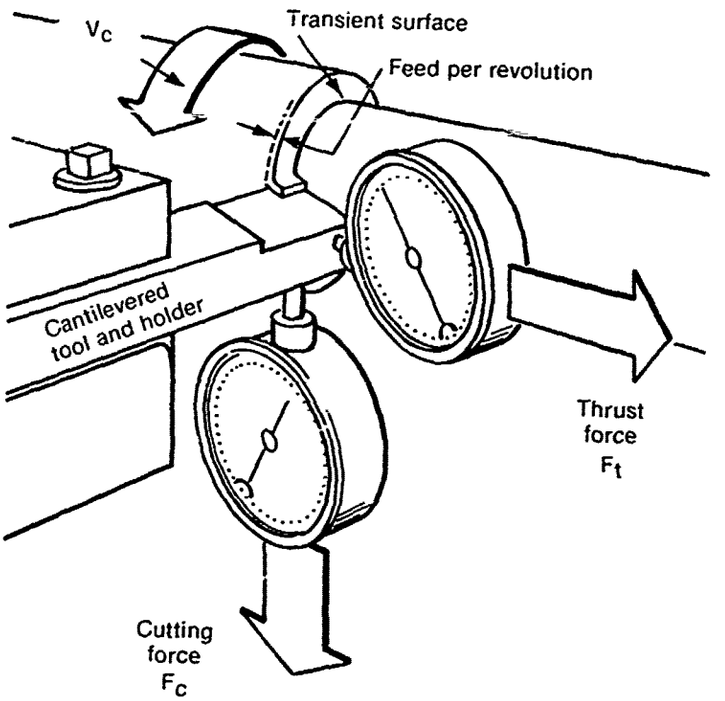
17.1 Determining Forces in Machining 17–3
17.2 Determining Power Requirements in Machining 17–7
17.3 Estimating Forces in Turning 17–23
17.4 Estimating Torque and Thrust in Drilling 17–27

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Determining Forces in Machining 17.1

The forces produced in turning and milling can be determined by the use of dynamometers such as those shown in figures 17.1-1 and 17.1-2. The drill dynamometer shown in figure 17.1-3 measures the torque and the thrust force.

The equations given in these three figures provide the means for calculating power and torque from the dynamometer readings in both English and metric units.



Determination of English Unit Parameters Using Unit hp Values

d = Depth of cut, in
D_t = Workpiece diameter, in
E = Efficiency of spindle drive
F_c = Cutting force, lb
f_r = Feed per revolution, in
hp_m = Horsepower at motor
hp_s = Horsepower at spindle
P = Unit power, hp/in³/min
Q = Metal removal rate, in³/min
T_s = Torque at spindle, in-lb
V_c = Cutting speed, fpm

$$hp_s = \frac{F_c \times V_c}{33{,}000}$$

$$hp_m = \frac{hp_s}{E}$$

$$Q = 12 \times d \times f_r \times V_c$$

$$P = \frac{hp_s}{Q}$$

$$T_s = F_c \times \frac{D_t}{2}$$

$$T_s = \frac{63{,}030 \times hp_s}{rpm}$$

Determination of Metric Unit Parameters Using Unit kW Values

d = Depth of cut, mm
D_t = Workpiece diameter, mm
E = Efficiency of spindle drive
F_c = Cutting force, N
f_r = Feed per revolution, mm
kW_m = Power at motor, kW
kW_s = Power at spindle, kW
P = Unit power, kW/cm³/min
Q = Metal removal rate, cm³/min
T_s = Torque at spindle, N·m
V_c = Cutting speed, m/min

$$kW_s = \frac{F_c \times V_c}{60{,}000}$$

$$kW_m = \frac{kW_s}{E}$$

$$Q = d \times f_r \times V_c$$

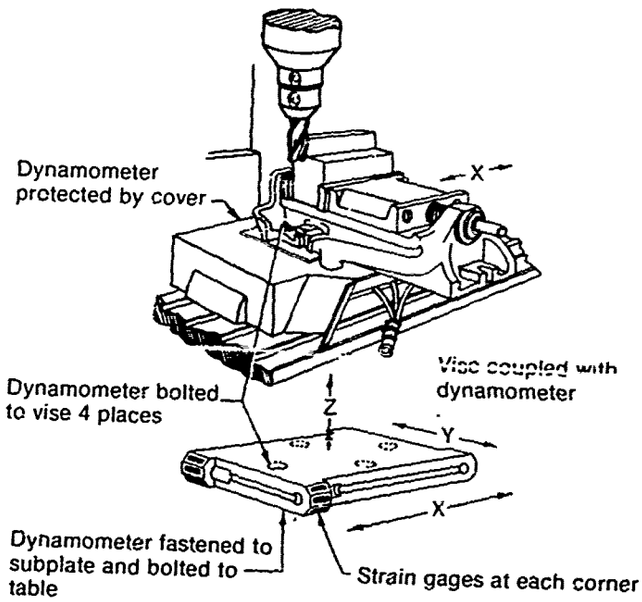
$$P = \frac{kW_s}{Q}$$

$$T_s = F_c \times \frac{D_t}{2000}$$

$$T_s = \frac{9549 \times kW_s}{rpm}$$

Figure 17.1-1 Forces and power in turning.

17.1 Determining Forces in Machining



Three-force dynamometer designed especially for measuring machining forces during milling (end milling shown).

Determination of English Unit Parameters Using Unit hp Values

d = Depth of cut, in
E = Efficiency of spindle drive
f_t = Feed, inch/tooth
n = Number of teeth in cutter
hp_m = Horsepower at motor
hp_s = Horsepower at spindle
P = Unit power, hp/in^3/min
Q = Metal removal rate, in^3/min
T_s = Torque at spindle, in-lb
V_c = Cutting speed, fpm
F_c = Cutting force, lb
w = Width of cut, in

$$hp_s = \frac{F_c \times V_c}{33{,}000}$$

$$hp_m = \frac{hp_s}{E}$$

$$Q = w \times d \times f_t \times n \times rpm$$

$$P = \frac{hp_s}{Q}$$

$$T_s = \frac{63{,}030 \times hp_s}{rpm}$$

Determination of Metric Unit Parameters Using Unit kW Values

d = Depth of cut, mm
E = Efficiency of spindle drive
f_t = Feed, mm/tooth
n = Number of teeth in cutter
kW_m = Power at motor, kW
kW_s = Power at spindle, kW
P = Unit power, kW/cm^3/min
Q = Metal removal rate, cm^3/min
T_s = Torque at spindle, N·m
V_c = Cutting speed, m/min
F_c = Cutting force, N
w = Width of cut, mm

$$kW_s = \frac{F_c \times V_c}{60{,}000}$$

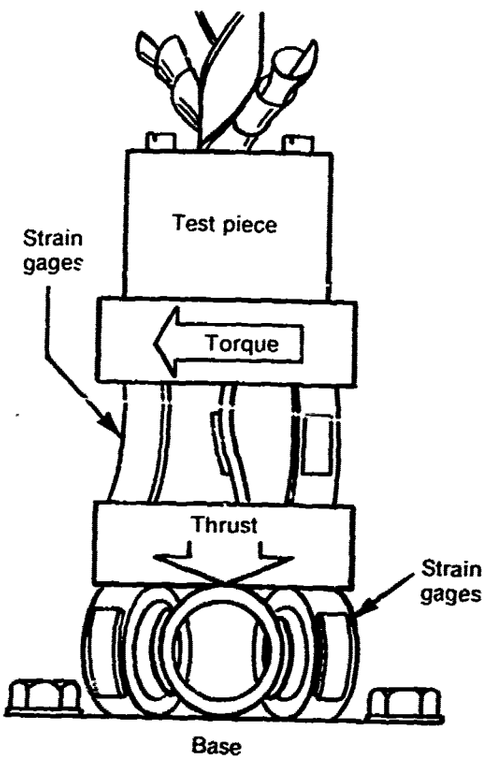
$$kW_m = \frac{kW_s}{E}$$

$$Q = \frac{w \times d \times f_t \times n \times rpm}{1000}$$

$$P = \frac{kW_s}{Q}$$

$$T_s = \frac{9549 \times kW_s}{rpm}$$

Figure 17.1–2 Forces and power in milling.



Determination of English Unit Parameters Using Unit hp Values

D_d = Drill diameter, in
E = Efficiency of spindle drive
f_r = Feed, inch/revolution
hp_s = Horsepower at motor
hp_m = Horsepower at spindle
P = Unit power, hp/in^3/min
Q = Metal removal rate, in^3/min
T_s = Torque at spindle, in-lb
V_c = Cutting speed

$$hp_s = \frac{T_s \times rpm}{63{,}030}$$

$$hp_m = \frac{hp_s}{E}$$

$$Q = \frac{\pi}{4} \times D_d^2 \times f_r \times rpm$$

$$P = \frac{hp_s}{Q}$$

$$T_s = 49{,}500 \times f_r \times D_d^2 \times P$$

Determination of Metric Unit Parameters Using kW Values

D_d = Drill diameter, mm
E = Efficiency of spindle drive
f_r = Feed, mm/revolution
kW_s = Power at spindle, kW
kW_m = Power at motor, kW
P = Unit power, kW/cm^3/min
Q = Metal removal rate, cm^3/min
T_s = Torque at spindle, N·m
V_c = Cutting speed, m/min

$$kW_s = \frac{T_s \times rpm}{9549}$$

$$kW_m = \frac{kW_s}{E}$$

$$Q = \frac{\pi \times D_d^2 \times f_r \times rpm}{4000}$$

$$P = \frac{kW_s}{Q}$$

$$T_s = 7.5 \times f_r \times D_d^2 \times P$$

Figure 17.1–3 Forces and power in drilling.

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Determining Power Requirements in Machining 17.2

The power required in machining can be determined by several different methods as follows:

Use of a watt meter or ammeter at the spindle motor. This is the simplest and most practical method of measuring power. The watt meter is more accurate and reaches greatest accuracy when the motor is loaded to full load. The power required at the cutter can be estimated by subtracting the idle power from the power produced while cutting.

Calculation of power from the cutting force. In order to utilize this method, it is necessary to measure the forces at the cutting tool using a dynamometer such as one shown in figure 17.1-1, 17.1-2 or 17.1-3. From the cutting force values, F_c, as measured with the turning dynamometer, the power at the spindle can be calculated. The power at the spindle in drilling can be calculated from the torque measured by the drill dynamometer in figure 17.1-3. To determine the power in milling, the torque must be measured with a torque dynamometer, and the power calculated from the torque values. The power at the motor is determined by dividing the power at the spindle by the efficiency of the spindle system. See figures 17.1-1 to 17.1-3 and the alignment chart, figure 17.2-11.

Calculation of power from published values of unit power requirements. An adequate estimate of power in machining can be made from the unit power requirements given in table 17.2-3 and figure 17.2-1 or table 17.2-4 and figure 17.2-2. The power is determined by multiplying the unit power requirements (hp/in^3/min or kW/cm^3/min) by the rate of metal removal (in^3/min or cm^3/min). The equations for performing these operations are given in tables 17.2-1 and 17.2-2. In addition, alignment charts are provided in figures 17.2-3 through 17.2-10 for determining the power required for turning, milling, drilling and broaching.

A list of the equations, data sheets, and alignment charts for determining the power requirements and other pertinent information on machining for both English and metric units is as follows:

Tables 17.2-1 and 17.2-2 – Shop Formulas for Turning, Milling, Drilling and Broaching

Tables 17.2-3 and 17.2-4 – Unit Power Requirements for Turning, Drilling and Milling

Figures 17.2-1 and 17.2-2 – Unit Power Requirements for Surface Broaching

Figures 17.2-3 and 17.2-4 – Alignment Chart for Determining Metal Removal Rate and Motor Power in Turning

Figures 17.2-5 and 17.2-6 – Alignment Chart for Determining Metal Removal Rate and Motor Power in Face Milling

Figures 17.2-7 and 17.2-8 – Alignment Chart for Determining Motor Power in Drilling

Figures 17.2-9 and 17.2-10 – Alignment Chart for Determining Metal Removal Rate and Motor Power in Surface Broaching

Figure 17.2-11 – Alignment Chart for Estimating Spindle Drive Efficiency

17.2 Determining Power Requirements in Machining

TABLE 17.2-1 Shop Formulas for Turning, Milling, Drilling and Broaching—English Units

PARAMETER	TURNING	MILLING	DRILLING	BROACHING
Cutting speed, fpm	$V_c = .262 \times D_t \times rpm$	$V_c = .262 \times D_m \times rpm$	$V_c = .262 \times D_d \times rpm$	V_c
Revolutions per minute	$rpm = 3.82 \times \frac{V_c}{D_t}$	$rpm = 3.82 \times \frac{V_c}{D_m}$	$rpm = 3.82 \times \frac{V_c}{D_d}$	—
Feed rate, in/min	$f_m = f_r \times rpm$	$f_m = f_t \times n \times rpm$	$f_m = f_r \times rpm$	—
Feed per tooth, in	—	$f_t = \frac{f_m}{n \times rpm}$	—	f_t
Cutting time, min	$t = \frac{L}{f_m}$	$t = \frac{L}{f_m}$	$t = \frac{L}{f_m}$	$t = \frac{L}{12\,V_c}$
Rate of metal removal, in^3/min	$Q = 12 \times d \times f_r \times V_c$	$Q = w \times d \times f_m$	$Q = \frac{\pi D^2 d}{4} \times f_m$	$Q = 12 \times w \times d \times V_c$
Horsepower required at spindle*	$hp_s = Q \times P$	$hp_s = Q \times P$	$hp_s = Q \times P$	—
Horsepower required at motor*	$hp_m = \frac{Q \times P}{E}$	$hp_m = \frac{Q \times P}{E}$	$hp_m = \frac{Q \times P}{E}$	$hp_m = \frac{Q \times P}{E}$
Torque at spindle	$T_s = \frac{63030\ hp_s}{rpm}$	$T_s = \frac{63030\ hp_s}{rpm}$	$T_s = \frac{63030\ hp_s}{rpm}$	—

SYMBOLS:
D_t = Diameter of workpiece in turning, inches
D_m = Diameter of milling cutter, inches
D_d = Diameter of drill, inches
d = Depth of cut, inches
d_t = Total depth per stroke in broaching, inches
E = Efficiency of spindle drive
f_m = Feed rate, inches per minute
f_r = Feed, inches per revolution
f_t = Feed, inches per tooth
hp_m = Horsepower at motor
hp_s = Horsepower at spindle
L = Length of cut, inches
n = Number of teeth in cutter
P = Unit power, horsepower per cubic inch per minute
Q = Rate of metal removed, cubic inches per minute
rpm = Revolutions per minute of work or cutter
T_s = Torque at spindle, inch-pounds
t = Cutting time, minutes
V_c = Cutting speed, feet per minute
w = Width of cut, inches

*Unit power data are given in table 17.2-3 for turning, milling and drilling, and in figure 17.2-1 for broaching.

TABLE 17.2–2 Shop Formulas for Turning, Milling, Drilling and Broaching—Metric Units

PARAMETER	TURNING	MILLING	DRILLING	BROACHING
Cutting speed, m/min	$V_c = \frac{\pi}{1000} \times D_t \times rpm$	$V_c = \frac{\pi}{1000} \times D_m \times rpm$	$V_c = \frac{\pi}{1000} \times D_d \times rpm$	V_c
Revolutions per minute	$rpm = \frac{1000}{\pi} \times \frac{V_c}{D_t}$	$rpm = \frac{1000}{\pi} \times \frac{V_c}{D_m}$	$rpm = \frac{1000}{\pi} \times \frac{V_c}{D_d}$	—
Feed rate, mm/min	$f_m = f_r \times rpm$	$f_m = f_t \times n \times rpm$	$f_m = f_r \times rpm$	—
Feed per tooth, mm	—	$f_t = \frac{f_m}{n \times rpm}$	—	f_t
Cutting time, min	$t = \frac{L}{f_m}$	$t = \frac{L}{f_m}$	$t = \frac{L}{f_m}$	$t = \frac{L}{1000 V_c}$
Rate of metal removal, cm^3/min	$Q = d \times f_r \times V_c$	$Q = \frac{w \times d \times f_m}{1000}$	$Q = \frac{\pi D_d^2}{4000} \times f_m$	$Q = w \times d_t \times V_c$
Power required at spindle*	$kW_s = Q \times P$	$kW_s = Q \times P$	$kW_s = Q \times P$	—
Power required at motor*	$kW_m = \frac{Q \times P}{E}$	$kW_m = \frac{Q \times P}{E}$	$kW_m = \frac{Q \times P}{E}$	$kW_m = \frac{Q \times P}{E}$
Torque at spindle	$T_s = \frac{9549 kW_s}{rpm}$	$T_s = \frac{9549 kW_s}{rpm}$	$T_s = \frac{9549 kW_s}{rpm}$	—

SYMBOLS. D_t = Diameter of workpiece in turning, millimeters
D_m = Diameter of milling cutter, millimeters
D_d = Diameter of drill, millimeters
d = Depth of cut, millimeters
d_t = Total depth per stroke in broaching, millimeters
E = Efficiency of spindle drive
f_m = Feed rate, millimeters per minute
f_r = Feed, millimeters per revolution
f_t = Feed, millimeters per tooth
kW_m = Power at motor, kW
kW_s = Power at spindle, kW
L = Length of cut, millimeters
n = Number of teeth in cutter
P = Unit power, kilowatts per cubic centimeter per minute
Q = Rate of metal removed, cubic centimeters per minute
rpm = Revolutions per minute of work or cutter
T_s = Torque at spindle, newton-meters
t = Cutting time, minutes
V_c = Cutting speed, meters per minute
w = Width of cut, millimeters

*Unit power data are given in table 17.2-4 for turning, milling and drilling, and in figure 17 2-2 for broaching.

17.2 Determining Power Requirements in Machining

TABLE 17.2–3 Average Unit Power Requirements for Turning, Drilling and Milling—English Units

MATERIAL	HARDNESS	UNIT POWER* hp/in³/min					
		TURNING P_t HSS AND CARBIDE TOOLS (feed .005-.020 ipr)		DRILLING P_d HSS DRILLS (feed .002-.008 ipr)		MILLING P_m HSS AND CARBIDE TOOLS (feed .005-.012 ipt)	
	Bhn	Sharp Tool	Dull Tool	Sharp Tool	Dull Tool	Sharp Tool	Dull Tool
STEELS, WROUGHT AND CAST Plain Carbon Alloy Steels Tool Steels	85-200	1.1	1 4	1.0	1 3	1.1	1.4
	35-40 R_c	1.4	1.7	1 4	1.7	1.5	1 9
	40-50 R_c	1.5	1.9	1.7	2.1	1.8	2.2
	50-55 R_c	2.0	2.5	2.1	2.6	2 1	2 6
	55-58 R_c	3 4	4.2	2 6	3.2†	2 6	3.2
CAST IRONS Gray, Ductile and Malleable	110-190	0.7	0.9	1.0	1.2	0.6	0.8
	190-320	1.4	1.7	1 6	2 0	1.1	1.4
STAINLESS STEELS, WROUGHT AND CAST Ferritic, Austenitic and Martensitic	135-275	1.3	1.6	1.1	1.4	1.4	1.7
	30-45 R_c	1.4	1.7	1.2	1 5	1.5	1.9
PRECIPITATION HARDENING STAINLESS STEELS	150-450	1.4	1.7	1.2	1 5	1.5	1.9
TITANIUM	250-375	1.2	1.5	1.1	1.4	1.1	1.4
HIGH TEMPERATURE ALLOYS Nickel and Cobalt Base	200-360	2.5	3 1	2.0	2.5	2.0	2.5
Iron Base	180-320	1 6	2.0	1 2	1 5	1.6	2.0
REFRACTORY ALLOYS Tungsten	321	2.8	3.5	2 6	3.3†	2.9	3.6
Molybdenum	229	2 0	2.5	1.6	2.0	1.6	2.0
Columbium	217	1.7	2.1	1.4	1.7	1 5	1.9
Tantalum	210	2.8	3.5	2.1	2.6	2.0	2.5
NICKEL ALLOYS	80-360	2.0	2.5	1.8	2 2	1.9	2.4
ALUMINUM ALLOYS	30-150 500 kg	0.25	0.3	0.16	0.2	0 32	0.4
MAGNESIUM ALLOYS	40-90 500 kg	0.16	0.2	0.16	0.2	0.16	0.2
COPPER	80 R_B	1 0	1 2	0.9	1.1	1.0	1.2
COPPER ALLOYS	10-80 R_B 80-100 R_B	0.64 1.0	0.8 1.2	0.48 0 8	0.6 1.0	0.64 1.0	0.8 1.2

*Power requirements at spindle drive motor, corrected for 80% spindle drive efficiency.

† Carbide

TABLE 17.2–4 Average Unit Power Requirements for Turning, Drilling and Milling—Metric Units

MATERIAL	HARDNESS	UNIT POWER* kW/cm³/min					
		TURNING P_t HSS AND CARBIDE TOOLS (feed .12-.50 mm/r)		DRILLING P_d HSS DRILLS (feed .05-.20 mm/r)		MILLING P_m HSS AND CARBIDE TOOLS (feed .12-.30 mm/r)	
	Bhn	Sharp Tool	Dull Tool	Sharp Tool	Dull Tool	Sharp Tool	Dull Tool
STEELS, WROUGHT AND CAST Plain Carbon Alloy Steels Tool Steels	85-200	0.050	0.064	0.046	0.059	0.050	0.064
	35-40 R_c	.064	.077	.064	.077	.068	.086
	40-50 R_c	.068	.086	.077	.096	.082	.100
	50-55 R_c	.091	.114	.096	.118	.096	.118
	55-58 R_c	.155	.191	.118	.146†	.118	.146
CAST IRONS Gray, Ductile and Malleable	110-190	.032	.041	.046	.055	.027	.036
	190-320	.064	.077	.073	.091	.050	.064
STAINLESS STEELS, WROUGHT AND CAST Ferritic, Austenitic and Martensitic	135-275	.059	.073	.050	.064	.064	.077
	30-45 R_c	.064	.077	.055	.068	.068	.086
PRECIPITATION HARDENING STAINLESS STEELS	150-450	.064	.077	.055	.068	.068	.086
TITANIUM	250-375	.055	.068	.050	.064	.050	.064
HIGH TEMPERATURE ALLOYS Nickel and Cobalt Base	200-360	.114	.141	.091	.114	.091	.114
Iron Base	180-320	.073	.091	.055	.068	.073	.091
REFRACTORY ALLOYS Tungsten	321	.127	.159	.118	.150†	.132	.164
Molybdenum	229	.091	.114	.073	.091	.073	.091
Columbium	217	.077	.096	.064	.077	.068	.086
Tantalum	210	.127	.159	.096	.118	.091	.114
NICKEL ALLOYS	80-360	.091	.114	.082	.100	.086	.109
ALUMINUM ALLOYS	30-150 500 kg	.011	.014	.007	.009	.015	.018
MAGNESIUM ALLOYS	40-90 500 kg	.007	.009	.007	.009	.007	.009
COPPER	80 R_B	.046	.055	.041	.050	.046	.055
COPPER ALLOYS	10-80 R_B 80-100 R_B	.029 .046	.036 .055	.022 .036	.027 .046	.029 .046	.036 .055

*Power requirements at spindle drive motor, corrected for 80% spindle drive efficiency.

† Carbide

17.2 Determining Power Requirements in Machining

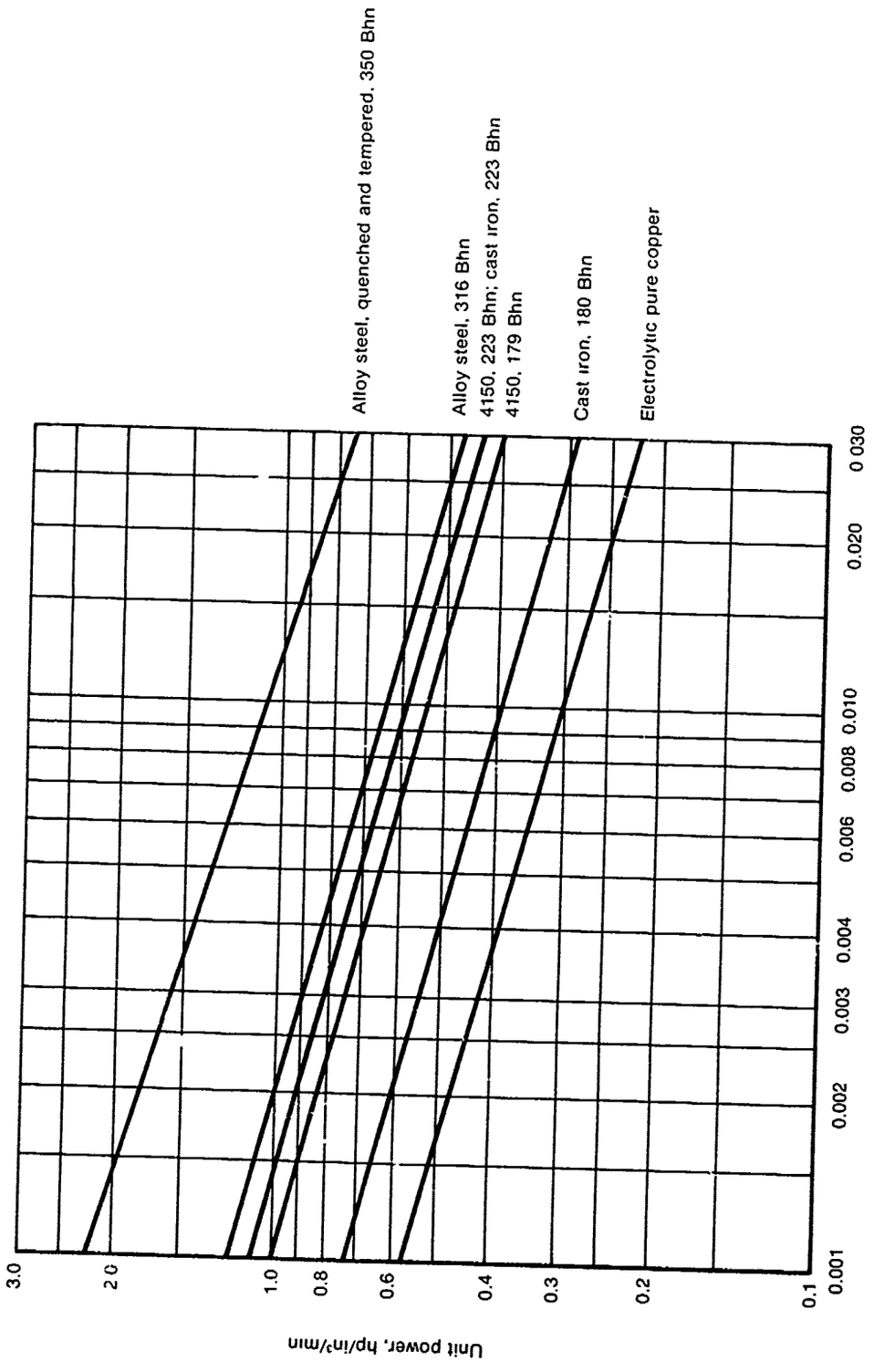


Figure 17.2-1 Unit power requirements for surface broaching with HSS tools only—English units.

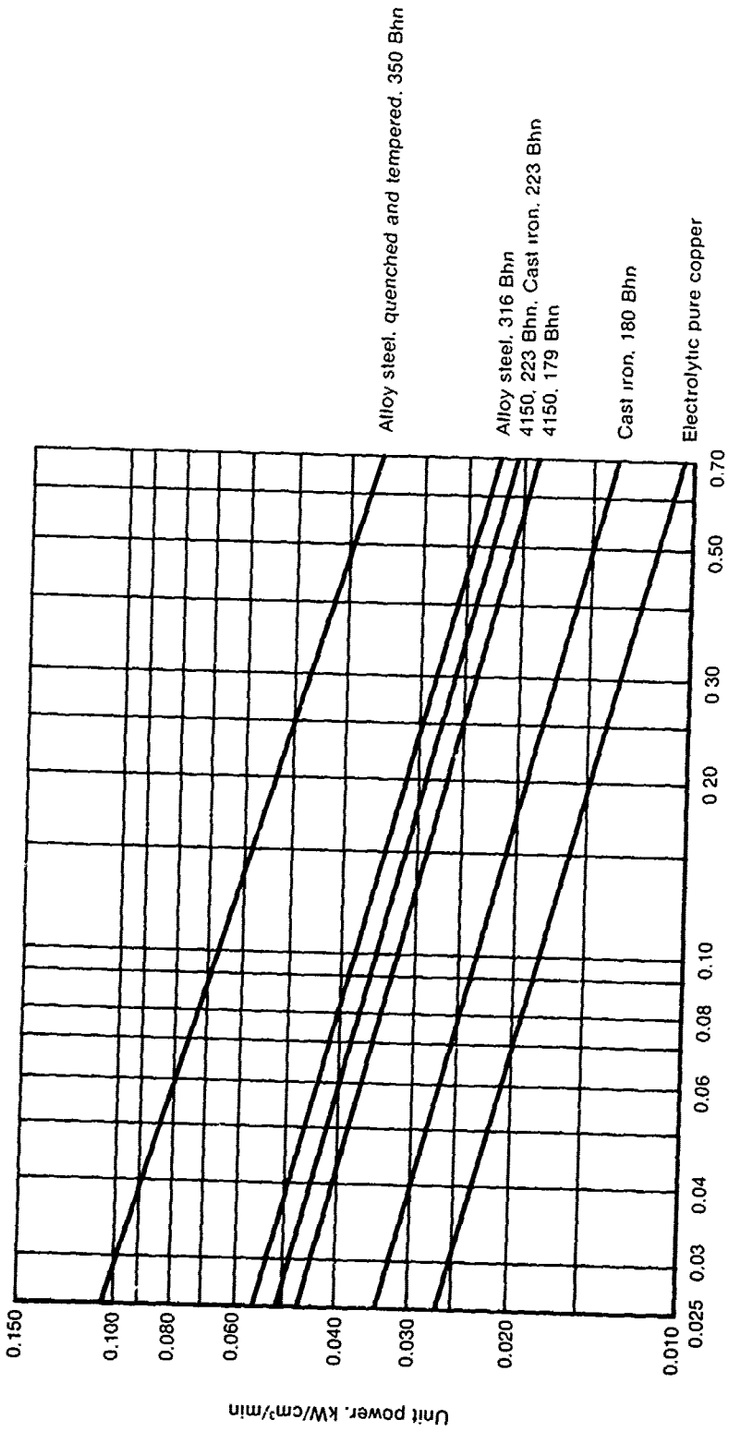
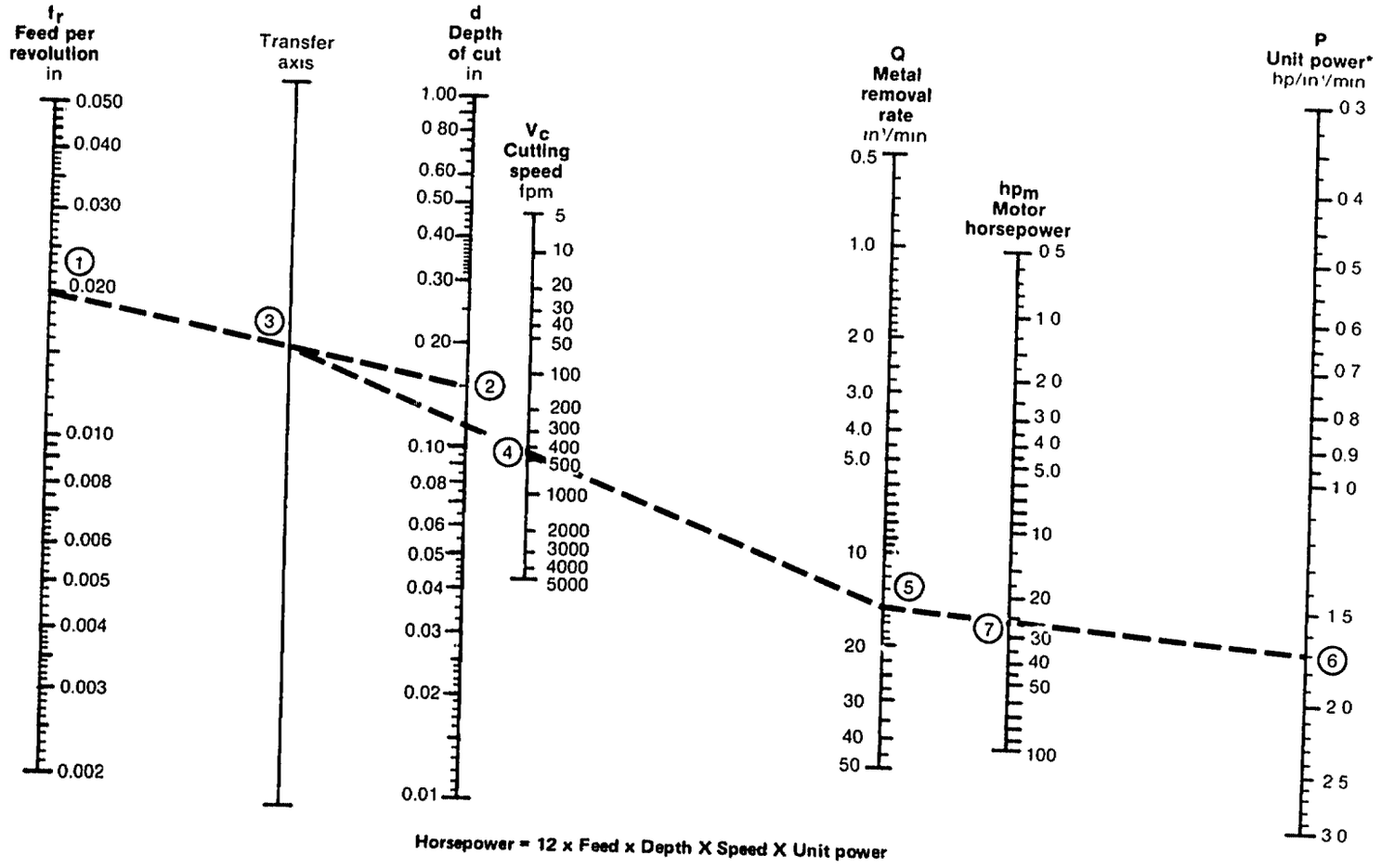


Figure 17.2-2 Unit power requirements for surface broaching with HSS tools only—Metric units.



Horsepower = 12 x Feed x Depth X Speed X Unit power

Example:

f_r = 0.020 in d = 0.150 in

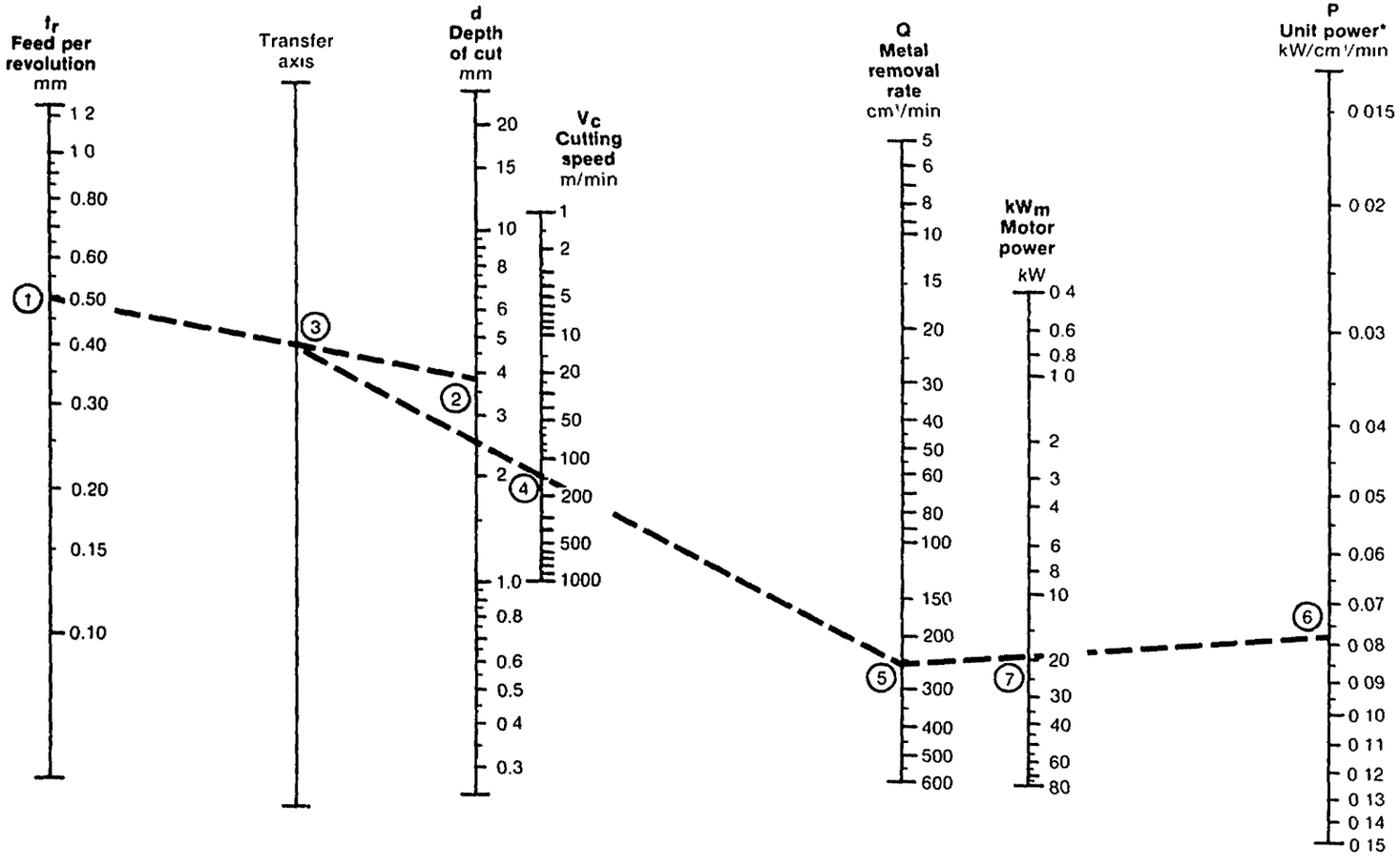
V_c = 425 fpm P = 1.70 hp/in³/min

* See table 17.2-3 for Unit power values. Corrected for dull cutter and 80% machine tool efficiency.

To Determine Motor Horsepower:

Connect Feed ① with Depth of cut ② to obtain point ③ on Transfer axis. Connect ③ with Cutting speed ④ to obtain point ⑤ on Metal removal rate scale. Connect point ⑤ with Unit power ⑥ to obtain 26 Motor horsepower at point ⑦

Figure 17.2-3 Alignment chart for determining metal removal rate and motor horsepower in turning—English units.



Power = Feed x Depth x Speed x Unit power

Example:

f_r = 0.5 mm d = 3.8 mm

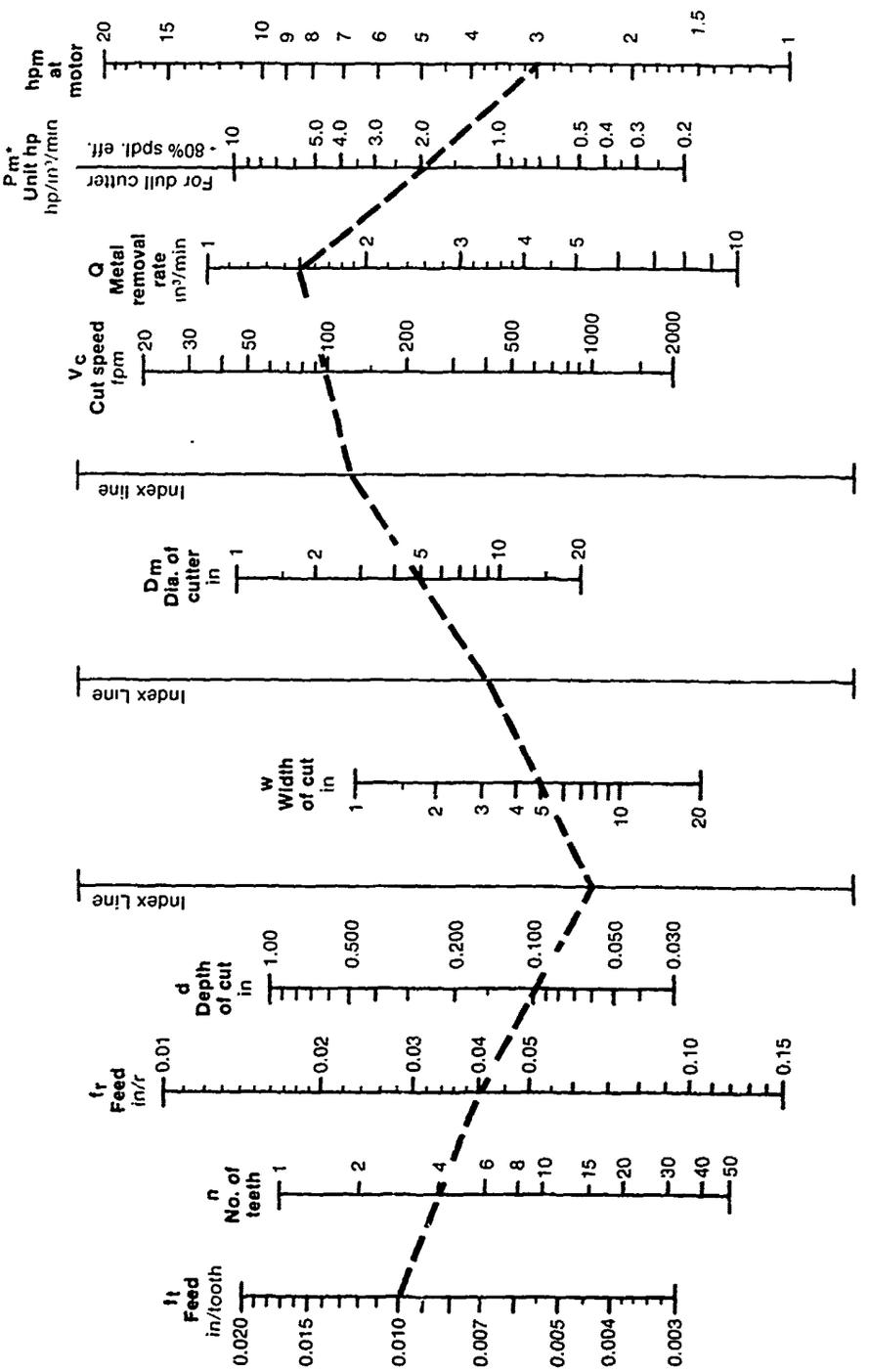
V_c = 130 m/min P = 0.077 kW/cm³/min

*See table 17.2-4 for Unit power values. Corrected for dull cutter and 80% machine tool efficiency.

To Determine Motor Power:

Connect Feed ① with Depth of cut ② to obtain point ③ on Transfer axis Connect ③ with Cutting speed ④ to obtain point ⑤ on Metal removal rate scale. Connect point ⑤ with Unit power ⑥ to obtain 19 02 kW at Motor, point ⑦

Figure 17.2-4 Alignment chart for determining metal removal rate and motor power in turning—Metric units.



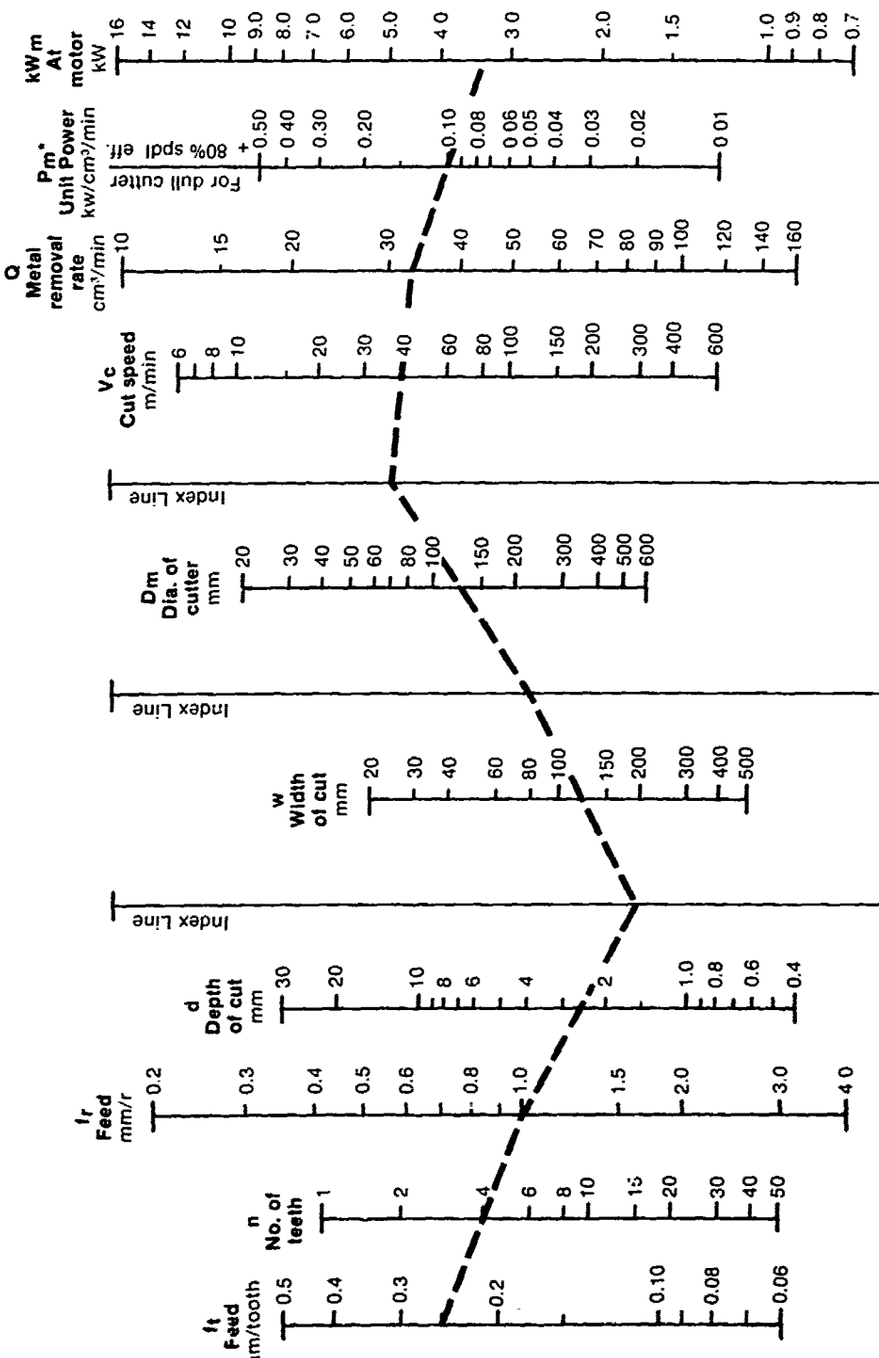
$$hp_m = \frac{P_m \times 3.82 \times f_t \times n \times d \times w \times V_c}{D_m}$$

*See table 17.2-3 for Unit power values

Example:

f_t = 0.010 in/tooth d = 0.100 in V_c = 100 fpm
n = 4 teeth w = 5 in Q = 1.53 in³/min
f_r = 0.04 in/r D_m = 5 in P_m = 2.0 hp/in³/min
hp_m = 3.0 hp

Figure 17.2-5 Alignment chart for determining metal removal rate and motor horsepower in face milling—English units.



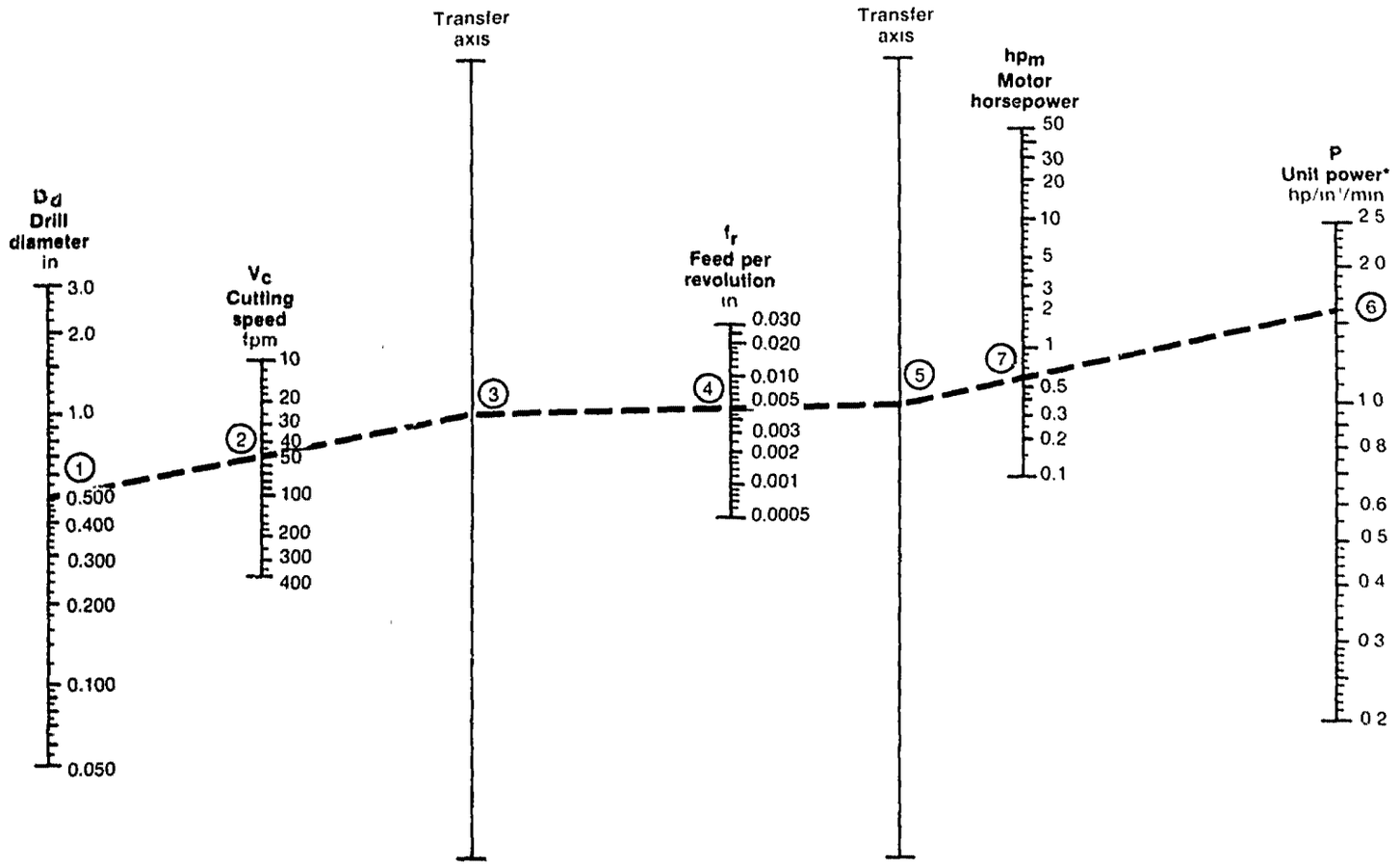
$$hp_m = \frac{P_m \times 318.3 \times f_t \times n \times d \times w \times V_c}{1000\ D_m}$$

*See table 17.2-4 for Unit power values

Example:

f_t = 0.25 mm/tooth — d = 2.5 mm — V_c = 40 m/min
n = 4 teeth — w = 125 mm — Q = 31.8 cm³/min
f_r = 1.0 mm/r — D_m = 125 mm — P_m = 0.1 kW/cm³/min
kW_m = 3.18 kW

Figure 17.2-6 Alignment chart for determining metal removal rate and motor power in face milling—Metric units.



Horsepower = 3 x Drill diameter x Speed x Feed x Unit power

Example:

D_d = 0.500 in f_r = 0.005 in

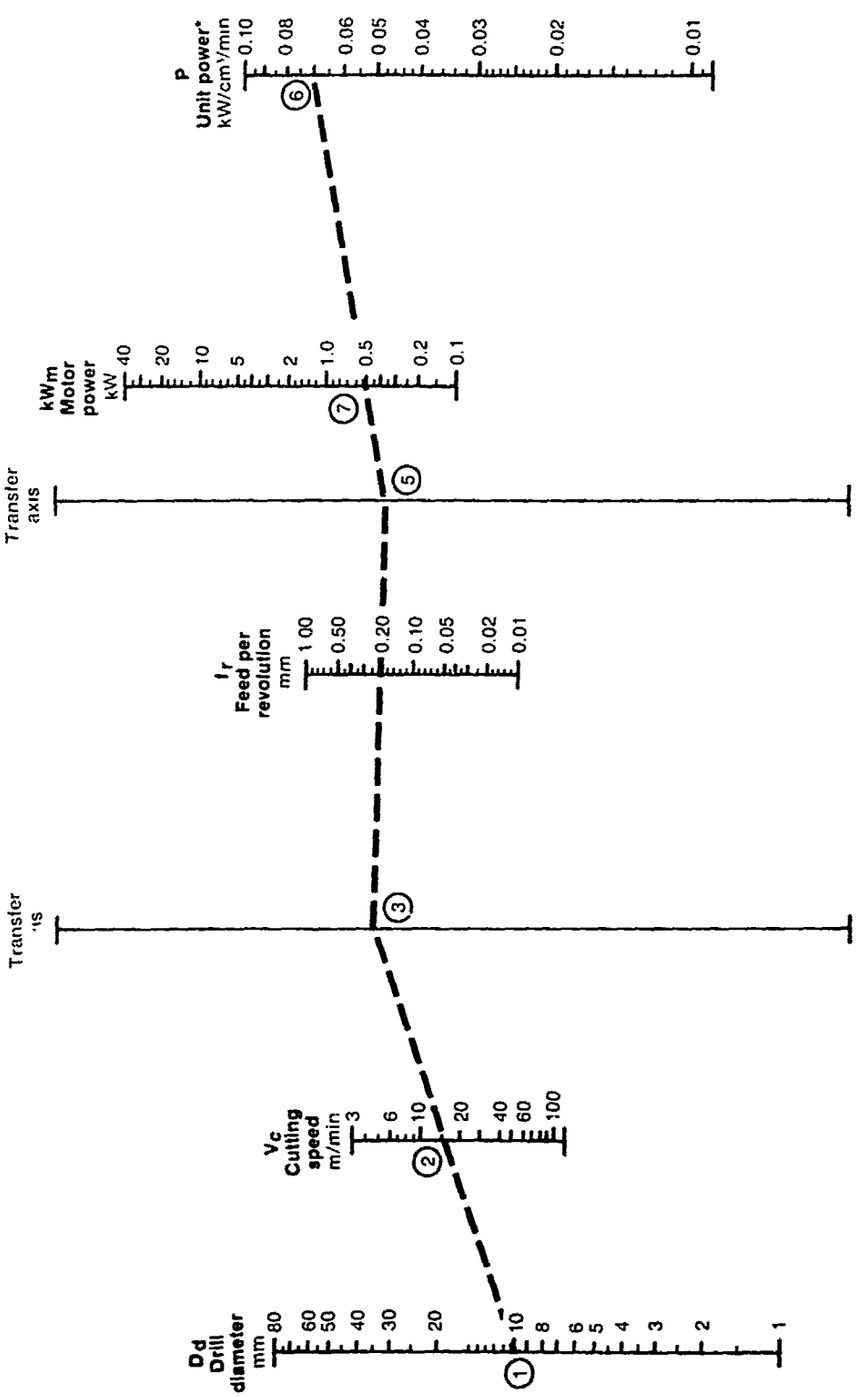
V_c = 50 fpm P = 1.6 hp/in³/min

*See table 17.2-3 for Unit power values. Corrected for dull drill and 80% machine tool efficiency.

To Determine Motor Horsepower:

Connect Drill diameter ① with Cutting speed ② to obtain point ③ on Transfer axis. Connect ③ with Feed ④ to obtain point ⑤ on Transfer axis. Connect ⑤ with Unit power ⑥ to obtain 0.60 Motor horsepower, point ⑦

Figure 17.2–7 Alignment chart for determining motor horsepower in drilling—English units.



Motor Power = 0.25 x Drill diameter x Speed x Feed x Unit Power

To Determine Motor Power:

Connect Drill diameter ① with Cutting speed ② to obtain point ③ on Transfer axis. Connect ③ with Feed ④ to obtain point ⑤ on Transfer axis. Connect ⑤ with Unit power ⑥ to obtain 0.53 kW at motor power, point ⑦

Example:

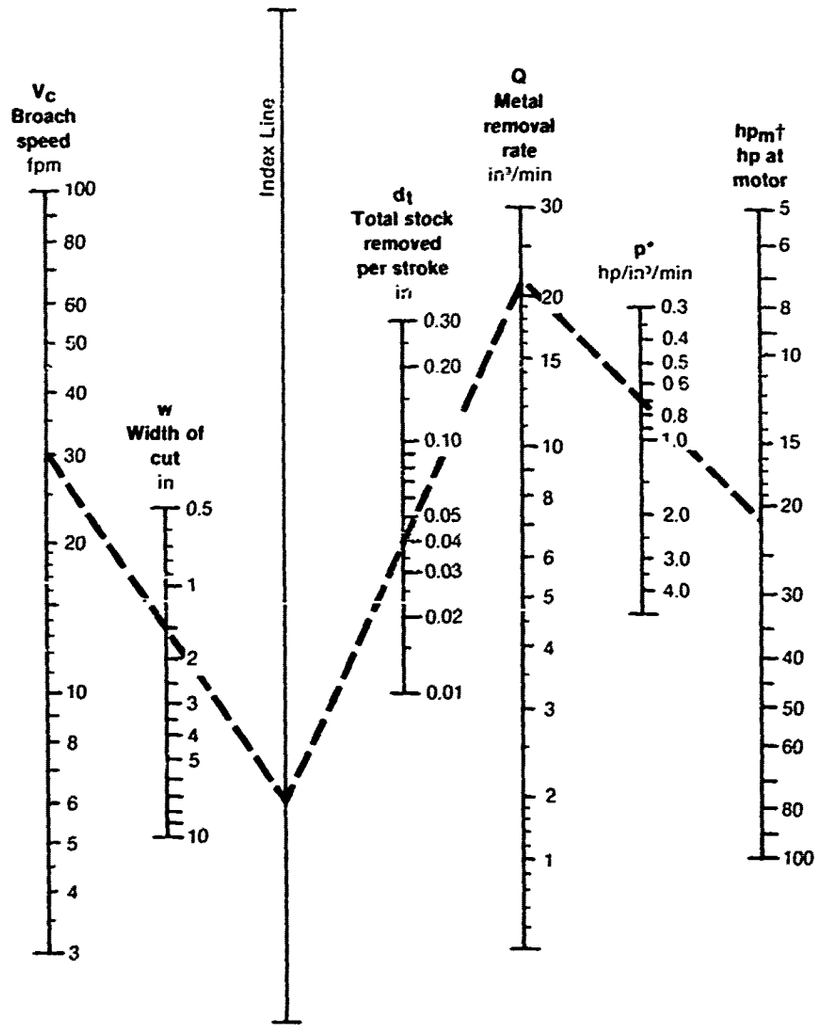
D_d = 10 mm f_r = 0.2 mm

V_c = 15 m/min P = 0.07 kW/cm³/min

*See table 17.2-4 for Unit power values. Corrected for dull drill and 80% machine tool efficiency.

Figure 17.2-8 Alignment chart for determining motor power in drilling—Metric units.

17.2 Determining Power Requirements in Machining



Example:

Material: Cast iron – HSS tools

Chipload 0.005 in/tooth

V_c = 30 fpm w = 1.5 in

d_t = 0.040 in Q = 22 in³/min

P = 0.7 hp/in³/min hp_m = 22 hp

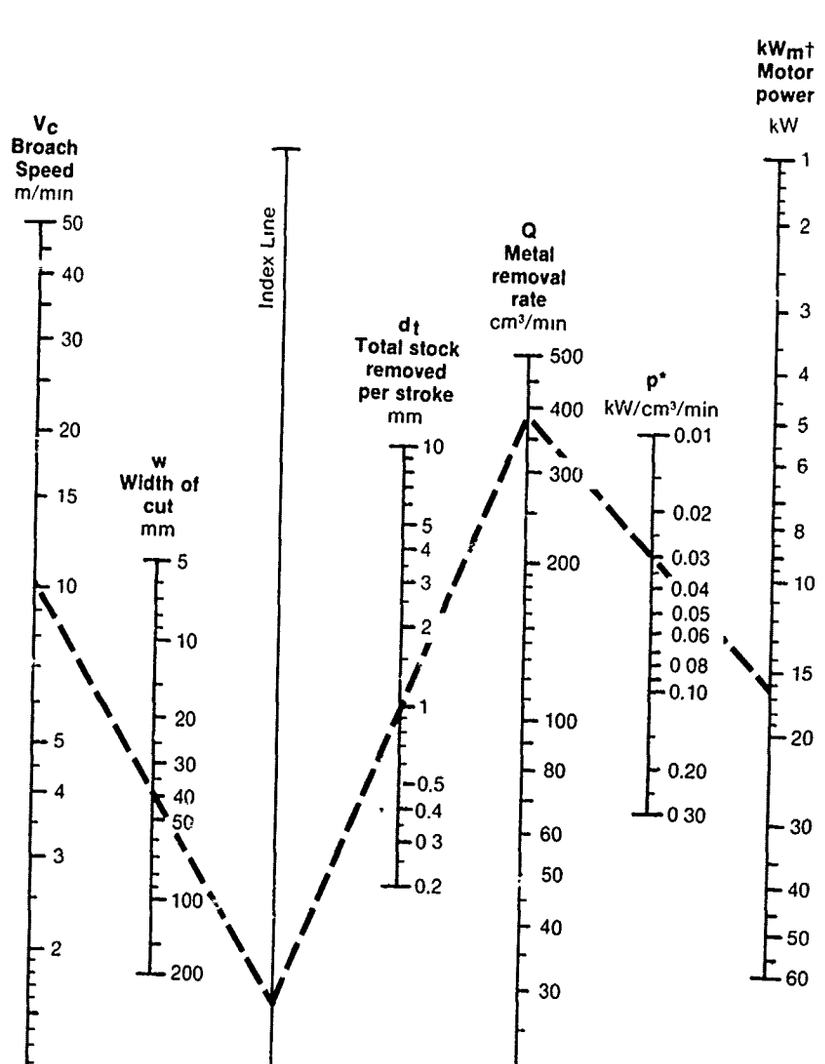
$$Q = 12 V_c \times w \times d_t \text{ in}^3/\text{min}$$

$$hp_m = \frac{Q \times P}{E} = \frac{Q \times P}{0.7}$$

*See figure 17.2-1 for Unit power values

†hp_m at motor for 70% drive efficiency

Figure 17.2–9 Alignment chart for determining metal removal rate and motor horsepower in surface broaching with high speed steel broaching tools—English units.



Example:

Material: Cast iron – HSS tools

Chipload 0.13 mm/tooth

V_c = 10 m/min

d_t = 1 mm

P = 0.03 kW/cm³/min

w = 38 mm

Q = 380 cm³/min

P_m = 16.3 kW

$$Q = V_c \times w \times d_t \text{ cm}^3/\text{min}$$

$$P_m = \frac{Q \times P}{E} = \frac{Q \times P}{0.7}$$

*See figure 17.2-2 for Unit power values

† kW_m at motor for 70% Drive Efficiency

Figure 17.2–10 Alignment chart for determining metal removal rate and motor power in surface broaching with high speed broaching tools—Metric units.

17.2 Determining Power Requirements in Machining

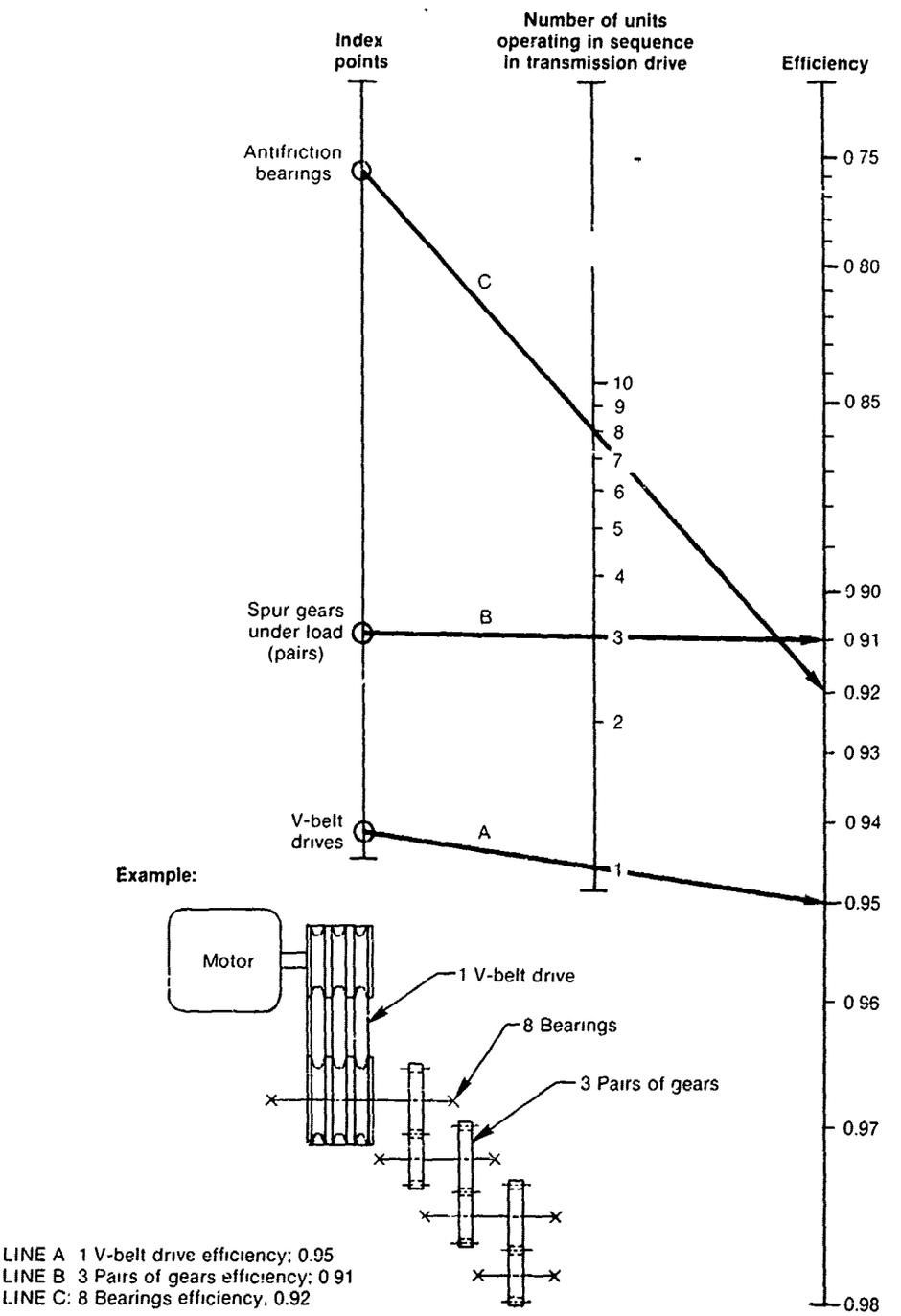


Figure 17.2–11 Alignment chart for estimating spindle drive efficiency.

Estimating Forces in Turning 17.3

The turning forces listed in tables 17.3-1 to 17.3-3 are based upon a systematic analysis of empirical data; nevertheless, these values are to be applied only as starting points. Most of the data were derived from the following sources:

Kaczmarek, J. 1976. *Principles of machining by cutting, abrasion and erosion.* Stevenage, England: Peter Peregrinus Ltd.

König, W. and Essel, K. 1973. *Spezifische Schnittkraftwerte für die Zerspanung metallischer Werkstoffe* (Cutting force data for the machining of metallic materials). Düsseldorf, West Germany: Verlag Stahleisen.

Kronenberg, M. 1966. *Machining science and application.* Oxford, England: Pergamon Press.

Zorev, N. N. 1966. *Metal cutting mechanics.* Oxford, England: Pergamon Press.

Metcut Research Associates Inc. Internal reports.

The forces listed are as follows:

Tangential or cutting force, F_t
Radial force, F_r
Feed force, F_f

The values in tables 17.3-1 to 17.3-3 provide the turning force in pounds for a unit depth of 1.0 inch. In order to calculate the estimated cutting force in pounds, multiply the values given in the tables by the depth of cut in inches (to convert to newtons, multiply force in pounds by 4.48222).

Example: Material: Steel, 175 Bhn
Rake angle: −5°
Side cutting edge angle (SCEA): 15°
Feed: 0.015 inch per revolution
Depth of cut: 0.250 inch

Read the following values from the force tables: F_t = 4890, F_r = 1648, F_f = 2500. Forces for this example are calculated as follows:

Tangential or cutting force = 4890 x 0.250 = 1223 pounds
Radial force = 1650 x 0.250 = 413 pounds
Feed force = 2500 x 0.250 = 625 pounds

TABLE 17.3-1 Turning Force Data for a Unit Depth of Cut of 1 Inch
(Data based on turning with carbide tool at 80 to 200 feet per minute)

MATERIAL AND HARDNESS	TOOL RAKE ANGLE degrees	FEED PER REV. in	SCEA: 0°			SCEA: 15°			SCEA: 30°			SCEA: 45°		
			F_t* lb	F_r† lb.	F_f‡ lb.	F_t lb.	F_r lb.	F_f lb.	F_t lb.	F_r lb.	F_f lb.	F_t lb.	F_r lb.	F_f lb.
Cast iron 260-320 Bhn	+5 to +10	.005	2,061	598	1,383	2,078	602	1,407	2,133	614	1,487	2,238	638	1,647
		.010	3,498	1,050	1,947	3,527	1,057	1,980	3,619	1,078	2,094	3,798	1,120	2,320
		.015	4,766	1,460	2,378	4,806	1,470	2,420	4,932	1,500	2,558	5,175	1,558	2,835
		.020	5,936	1,844	2,742	5,985	1,856	2,790	6,142	1,895	2,950	6,445	1,968	3,268
		.025	7,038	2,211	3,062	7,096	2,225	3,116	7,282	2,272	3,293	7,640	2,360	3,648
		.030	8,088	2,564	3,350	8,155	2,580	3,410	8,370	2,634	3,603	8,780	2,736	3,992
		040	10,074	3,240	3,862	10,157	3,260	3,930	10,424	3,328	4,153	10,937	3,457	4,602
		.050	11,944	3,883	4,312	12,043	3,908	4,388	12,358	3,990	4,637	12,966	4,144	5,138
	−5 to −10	.005	2,680	1,016	2,418	2,702	1,023	2,461	2,773	1,044	2,600	2,910	1,084	2,882
		.010	4,548	1,785	3,407	4,585	1,796	3,467	4,706	1,833	3,664	4,937	1,904	4,060
		.015	6,197	2,480	4,162	6,248	2,497	4,236	6,412	2,548	4,476	6,727	2,648	4,960
		.020	7,718	3,135	4,798	7,780	3,155	4,882	7,985	3,220	5,160	8,378	3,345	5,717
		.025	9,150	3,756	5,357	9,226	3,783	5,450	9,467	3,860	5,760	9,933	4,010	6,383
		.030	10,516	4,358	5,862	10,603	4,387	5,965	10,880	4,478	6,30-	11,416	4,650	6,985
		.040	13,097	5,507	6,757	13,205	5,543	6,876	13,550	5,657	7,267	14,218	5,876	8,052
		.050	15,528	6,602	7,544	15,656	6,645	7,677	16,066	6,782	8,113	16,857	7,044	8,990

NOTE: To calculate force in pounds, multiply values given by depth of cut in inches. To convert to newtons, multiply force in pounds by 4.48222.

*F_t = Tangential or Cutting force
†F_r = Radial force
‡F_f = Feed force

17.3 Estimating Forces in Turning

TABLE 17.3–2 Turning Force Data for a Unit Depth of ... 1 Inch
(Data based on turning with carbide tool at 200 to 600 feet per ...e)

MATERIAL AND HARDNESS	TOOL RAKE ANGLE degrees	FEED PER REV. in	SCEA: 0°			SCEA: 15°			SCEA: 30°			SCEA: 45°		
			F_t* lb.	F_r† lb.	F_f‡ lb.	F_t lb	F_r lb.	F_f lb	F_t lb.	F_r lb.	F_f lb.	F_t lb.	F_r lb.	F_f lb.
Cast iron 160-200 Bhn	+5 to +10	.005	1,195	340	300	1,204	343	813	1,232	350	857	1,288	362	946
		.010	2,056	608	1,140	2,070	610	1,160	2,120	623	1,224	2,216	644	1,350
		.015	2,824	852	1,405	2,845	857	1,430	2,913	873	1,507	3,044	903	1,663
		.020	3,538	1,082	1,629	3,564	1,088	1,657	3,650	1,108	1,747	3,814	1,147	1,928
		.025	4,213	1,303	1,827	4,245	1,310	1,858	4,347	1,335	1,960	4,542	1,380	2,162
		.030	4,860	1,517	2,006	4,897	1,525	2,040	5,014	1,554	2,152	5,240	1,607	2,375
		.040	6,088	1,927	2,326	6,134	1,938	2,365	6,280	1,974	2.494	6,563	2,042	2,753
		.050	7,250	2,320	2,608	7,305	2,334	2,653	7,480	2,377	2,797	7,816	2,458	3,087
	−5 to −10	.005	1,555	590	1,400	1,566	593	1,424	1,604	604	1,502	1,676	625	1,658
		.010	2,675	1,050	2,000	2,695	1,056	2,034	2,760	1,075	2,145	2,884	1,112	2,367
		015	3,675	1,470	2,463	3,703	1,480	2,505	3,790	1,507	2,640	3,962	1,558	2,915
		.020	4,603	1,868	2,855	4,638	1,880	2,903	4,750	1,914	3,062	4,963	1,980	3,378
		.025	5,482	2,250	3,202	5,523	2,263	3,256	5,656	2,304	3,434	5,910	2,385	3,790
		.030	6,323	2,618	3,516	6,371	2,634	3,576	6,524	2,683	3,770	6,817	2,775	4,160
		.040	7,920	3,327	4,076	7,980	3,346	4,145	8,172	3,408	4,370	8,540	3,526	4,824
		.050	9,433	4,006	4,570	9,504	4,030	4,648	9,732	4,104	4,902	10,170	4,246	5,410
Cast iron 200-260 Bhn	+5 to +10	.005	1,636	474	1,097	1,649	477	1,116	1,692	486	1,180	1,775	505	1,306
		.010	2,780	833	1,546	2,804	838	1,573	2,876	856	1,662	3,016	888	1,840
		.015	3,793	1,160	1,890	3,824	1,167	1,924	3,923	1,190	2,032	4,114	1,236	2,250
		.020	4,727	1,466	2,180	4,765	1,476	2,218	4,890	1,506	2,344	5,127	1,563	2,596
		.025	5,607	1,758	2,435	5,653	1,770	2,478	5,800	1,806	2,618	6,082	1,875	2,900
		.030	6,447	2,040	2,665	6,500	2,054	2,712	6,668	2,096	2,866	6,993	2,176	3,174
		.040	8,034	2,580	3,073	8,100	2,597	3,128	8,310	2,650	3,305	8,715	2,750	3,660
		.050	9,530	3,095	3,433	9,608	3,115	3,493	9,858	3,178	3,690	10,338	3,300	4,088
	−5 to −10	.005	2,126	806	1,918	2,143	811	1,952	2,200	828	2,062	2,306	860	2,284
		.010	3,614	1,418	2,704	3,644	1,427	2,752	3,738	1,457	2,908	3,920	1,512	3,220
		.015	4,930	1,974	3,306	4,970	1,987	3,364	5,098	2,027	3,555	5,347	2,104	3,938
		.020	6,144	2,495	3,813	6,194	2,511	3,880	6,355	2,563	4,100	6,664	2,660	4,540
		.025	7,288	2,993	4,258	7,348	3,012	4,334	7,538	3,074	4,578	7,905	3,190	5,072
		.030	8,380	3,473	4,660	8,448	3,495	4,743	8,668	3,566	5,012	9,090	3,703	5,552
		.040	10,444	4,390	5,375	10,530	4,418	5,470	10,803	4,508	5,780	11,328	4,680	6,402
		.050	12,390	5,200	6,004	12,490	5,300	6,110	12,815	5,408	6,456	13,438	5,615	7,150

NOTE: To calculate force in pounds, multiply values given by depth of cut in inches. To convert to newtons, multiply force in pounds by 4.48222.

*F_t = Tangential or Cutting force

†F_r = Radial force

‡F_f = Feed force

TABLE 17.3–3 Turning Force Data for a Unit Depth of Cut of 1 Inch
(Data based on turning with carbide tool at 300 to 600 feet per minute)

MATERIAL AND HARDNESS	TOOL RAKE ANGLE degrees	FEED PER REV. in	SCEA: 0°			SCEA: 15°			SCEA: 30°			SCEA: 45°		
			F_t* lb	F_r† lb.	F_f‡ lb.	F_t lb	F_r lb.	F_f lb	F_t lb	F_r lb.	F_f lb.	F_t lb	F_r lb.	F_f lb.
Steels 135-200 Bhn	+5 to +10	005	1,853	541	1,116	1,870	552	1,146	1,928	588	1,244	2,038	662	1,449
		010	3,062	725	1,324	3,092	740	1,360	3,186	788	1,476	3,369	886	1,719
		.015	4,108	860	1,463	4,148	877	1,502	4,274	934	1,630	4,520	1,050	1,900
		020	5,060	970	1,570	5,110	990	1,612	5,265	1,055	1,750	5,567	1,186	2,039
		.025	5,950	1,066	1,660	6,006	1,088	1,703	6,190	1,158	1,850	6,545	1,303	2,155
		030	6,790	1 150	1,736	6,855	1,174	1,782	7,064	1,250	1,934	7,469	1,407	2,254
		.040	8,365	1,300	1,863	8,444	1,326	1,912	8,702	1,412	2,076	9,200	1,588	2,420
		.050	9,832	1,427	1,968	9,927	1,456	2,020	10,230	1,550	2,194	10,816	1,744	2,556
	−5 to −10	.005	2,136	860	1,646	2,155	873	1,682	2,215	914	1,804	2,333	996	2,054
		.010	3,582	1,285	2,112	3,614	1,304	2,160	3,715	1,365	2,316	3,911	1,488	2,037
		.015	4,846	1,624	2,444	4,890	1,648	2,500	5,027	1,726	2,680	5,293	1,880	3,050
		.020	6,006	1,918	2,711	6,060	1,946	2,772	6,230	2,038	2,973	6,560	2,220	3,384
		.025	7,093	2,182	2,938	7,156	2,215	3,004	7,358	2,318	3,222	7,747	2,526	3,668
		.030	8,127	2,425	3,138	8,198	2,460	3,208	8,430	2,577	3,440	8,875	2,807	3,917
		.040	10,070	2,864	3,480	10,160	2,906	3,558	10,446	3,043	3,816	11,000	3,315	4,344
		.050	11,895	3,258	3,772	12,000	3,306	3,856	12,338	3,462	4,135	12,990	3,771	4,708
Steels 200-325 Bhn	+5 to +10	.005	1,942	497	1,183	1,960	504	1,213	2,015	529	1,313	2,121	577	1,522
		010	3,256	738	1,429	3,285	748	1,466	3,378	785	1,587	3,556	856	1,838
		015	4,405	929	1,596	4,444	943	1,638	4,570	988	1,773	4,812	1,078	2,054
		.020	5,460	1,095	1,727	5,508	1,111	1,772	5,662	1,165	1,918	5,963	1,270	2,222
		025	6,447	1,243	1,836	6,504	1,262	1,882	6,688	1,323	2,038	7,042	1,443	2,362
		.030	7,386	1,380	1,930	7,452	1,400	1,980	7,662	1,467	2,142	8,067	1,600	2,483
		.040	9,153	1,625	2,088	9,234	1,650	2,140	9,494	1,728	2,318	9,997	1,886	2,686
		050	10,810	1,845	2,218	10,905	1,872	2,275	11,212	1,963	2,463	11,806	2,142	2,854
	−5 to −10	.005	2,192	1,040	1,842	2,214	1,058	1,888	2,285	1,117	2,038	2,422	1,235	2,350
		010	3,592	1,478	2,262	3,628	1,504	2,318	3,743	1,587	2,503	3,968	1,754	2,886
		015	4,795	1,815	2,551	4,842	1,846	2,614	4,997	1,948	2,823	5,297	2,154	3,256
		.020	5,885	2,100	2,779	5,945	2,136	2,848	6,134	2,254	3,075	6,502	2,491	3,546
		.025	6,900	2,350	2,969	6,969	2,390	3,042	7,191	2,523	3,285	7,623	2,790	3,788
		.030	7,857	2,578	3,134	7,936	2,622	3,212	8,189	2,767	3,468	8,680	3,058	4,000
		.040	9,644	2,982	3,414	9,740	3,033	3,498	10,052	3,200	3,777	10,655	3,538	4,356
		050	10,306	3,338	3,647	11,420	3,395	3,737	11,784	3,584	4,036	12,490	3,962	4,654

NOTE: To calculate force in pounds, multiply values given by depth of cut in inches. To convert to newtons, multiply force in pounds by 4.48222

*F_t = Tangential or Cutting force

†F_r = Radial force

‡F_f = Feed force

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Estimating Torque and Thrust in Drilling 17.4

Tables 17.4-1 and 17.4-2 are tabulations of drilling torque and thrust values in English units derived from formulas given in the paper "On the drilling of metals. 2—The torque and thrust in drilling" by M. C. Shaw and C. J. Oxford, Jr., *Transactions of the ASME* 79 (January 1957), p. 139-148.

Example: Find the torque and thrust when drilling steel at 200 Bhn with a 1/2-inch diameter standard point drill using a feed rate of 0.006 inch per revolution.

In the table for standard point drills, locate 200 Bhn steel, read down the data column for a 1/2-inch drill to the 0.006-inch feed per revolution and read 124 inch-pounds torque and 735 pounds thrust

Tables 17.4-3 and 17.4-4 give torque and thrust values for the same materials in metric units.

TABLE 17.4-1 Torque and Thrust Values for Drilling with Standard Point Drills

MATERIAL AND HARDNESS	FEED PER REV.	TORQUE, inch-pounds								THRUST, pounds							
		Drill Diameter, in								Drill Diameter, in							
	in	⅛	¼	½	¾	1	1¼	1½	2	⅛	¼	½	¾	1	1¼	1½	2
Steels	0 0005	1.4	—	—	—	—	—	—	—	44	—	—	—	—	—	—	—
200 Bhn	001	2.5	8.5	—	—	—	—	—	—	65	130	—	—	—	—	—	—
	002	4.4	15	52	—	—	—	—	—	102	194	382	—	—	—	—	—
	.003	6	21	71	—	—	—	—	—	135	250	478	—	—	—	—	—
	004	8	26	90	183	—	—	—	—	166	304	568	832	—	—	—	—
	.006	11	36	124	253	414	617	856	1,430	224	403	735	1,058	1,368	1,687	2,030	2,796
	.008	—	45	156	318	521	776	1,078	1,800	—	496	891	1 269	1,629	1,997	2,388	3,246
	.010	—	54	187	381	623	928	1,288	2,152	—	584	1,039	1,469	1,876	2,292	2,728	3,674
	.012	—	—	216	440	721	1,074	1,491	2,490	—	—	1,182	1,662	2,115	2,575	3,054	4,085
	.015	—	—	259	527	862	1,283	1,782	2,976	—	—	1,387	1,939	2,458	2,983	3,524	4,677
	.020	—	—	325	663	1,085	1,615	2,243	3,746	—	—	1,711	2,378	3,001	3,629	4,269	5,614
	.025	—	—	—	—	1,297	1,931	2,681	4,478	—	—	—	—	3,517	4,244	4,976	6,505
	.030	—	—	—	—	—	—	—	5,782	—	—	—	—	—	—	—	7,360
Steels	0.0005	1.9	—	—	—	—	—	—	—	56	—	—	—	—	—	—	—
300 Bhn	.001	3.2	11	—	—	—	—	—	—	84	168	—	—	—	—	—	—
	002	5.6	19	67	—	—	—	—	—	132	251	494	—	—	—	—	—
	.003	7.8	27	92	—	—	—	—	—	175	324	618	—	—	—	—	—
	.004	9	33	116	236	—	—	—	—	215	293	733	1,075	—	—	—	—
	.006	14	46	160	327	535	796	1,106	1,847	290	521	950	1,367	1,767	2,179	2,622	3,611
	.008	—	58	202	411	673	1,003	1,392	2,325	—	640	1,151	1,639	2,104	2,580	3,084	4,193
	.010	—	70	241	492	805	1,199	1,664	2,779	—	754	1,342	1,898	2,424	2,961	3,523	4,745
	.012	—	—	279	569	932	1,386	1,925	3,216	—	—	1,526	2,146	2,732	3,327	3,945	5,276
	.015	—	—	334	680	1,114	1,658	2,302	3,844	—	—	1,791	2,504	3,175	3,854	4,552	6,041
	.020	—	—	420	856	1,402	2,087	2,897	4,839	—	—	2,211	3,071	3,876	4,688	5,514	7,251
	.025	—	—	—	—	1,676	2,495	3,463	5,785	—	—	—	—	4,543	5,481	6,428	8,402
	.030	—	—	—	—	—	—	—	6,693	—	—	—	—	—	—	—	9,507
Steels	0005	2	—	—	—	—	—	—	—	62	—	—	—	—	—	—	—
400 Bhn	.001	3.5	12	—	—	—	—	—	—	92	185	—	—	—	—	—	—
	.002	6.2	21	73	—	—	—	—	—	144	274	542	—	—	—	—	—
	.003	8.5	29	101	—	—	—	—	—	192	355	678	—	—	—	—	—
	004	11	37	127	259	—	—	—	—	236	431	805	1,179	—	—	—	—
	006	15	51	176	358	586	874	1,213	2,026	318	571	1,041	1,499	1,940	2,390	2,876	3,961
	.008	—	64	222	451	739	1,100	1,527	2,550	—	702	1,262	1,797	2,307	2,829	3,383	4,598
	.010	—	76	265	539	883	1,314	1,825	3,048	—	827	1,472	2,081	2,659	3,247	3,864	5,204
	012	—	—	306	624	1,022	1,521	2,112	3,527	—	—	1,674	2,354	2,996	3,648	4,327	5,787
	015	—	—	366	746	1,221	1,818	2,524	4,216	—	—	1,965	2,747	3,482	4,227	4,993	6,625
	.020	—	—	461	939	1,537	2,289	3,178	5,307	—	—	2,425	3,368	4,251	5,142	6,047	7,953
	.025	—	—	—	—	1,838	2,736	3,799	6,345	—	—	—	—	4,982	6,012	7,050	9,215
	030	—	—	—	—	—	—	—	7,341	—	—	—	—	—	—	—	10,430

17.4 Estimating Torque and Thrust in Drilling

TABLE 17.4–1—Continued

MATERIAL AND HARDNESS	FEED PER REV.	TORQUE, inch-pounds								THRUST, pounds							
		Drill Diameter, in								Drill Diameter, in							
	in	⅛	¼	½	¾	1	1¼	1½	2	⅛	¼	½	¾	1	1¼	1½	2
Aluminum Alloys	0005	0.4	—	—	—	—	—	—	—	13	—	—	—	—	—	—	—
	.001	0 7	2 5	—	—	—	—	—	—	19	38	—	—	—	—	—	—
	002	1.3	4.3	15	—	—	—	—	—	30	56	111	—	—	—	—	—
	.003	1.8	6	21	—	—	—	—	—	39	73	139	—	—	—	—	—
	004	2.2	7 6	26	53	—	—	—	—	49	89	166	243	—	—	—	—
	006	3.1	11	36	74	121	180	250	417	66	118	214	308	399	492	592	815
	.008	—	13	46	93	152	226	314	525	—	145	260	370	475	583	696	947
	010	—	16	55	111	182	271	376	628	—	170	303	428	547	669	796	1,072
	.012	—	—	63	128	210	313	435	726	—	—	345	485	617	751	891	1,191
	015	—	—	75	154	251	324	520	868	—	—	404	566	717	870	1,028	1,364
	.020	—	—	95	193	317	471	654	1,093	—	—	499	694	875	1,059	1,245	1,637
	.025	—	—	—	—	378	563	782	1,306	—	—	—	—	1,026	1,238	1,451	1,897
	.030	—	—	—	—	—	—	—	1,511	—	—	—	—	—	—	—	2,147
Magnesium Alloys	.0005	0.2	—	—	—	—	—	—	—	7.3	—	—	—	—	—	—	—
	001	0.4	1.4	—	—	—	—	—	—	11	22	—	—	—	—	—	—
	.002	0.7	2.5	8.6	—	—	—	—	—	17	32	64	—	—	—	—	—
	.003	1	3 4	12	—	—	—	—	—	23	42	80	—	—	—	—	—
	004	1.3	4.3	15	30	—	—	—	—	28	51	95	139	—	—	—	—
	.006	1.7	6	21	42	69	103	143	238	33	59	109	158	205	254	307	427
	008	—	7.5	26	53	87	129	180	300	—	83	148	211	272	333	398	541
	010	—	9	31	64	104	155	215	359	—	97	173	245	313	382	455	612
	.012	—	—	36	73	120	179	250	415	—	—	197	277	352	429	509	681
	.015	—	—	43	89	144	214	297	496	—	—	231	323	410	497	587	780
	.020	—	—	54	110	181	269	374	624	—	—	285	396	500	605	711	936
	.025	—	—	—	—	216	322	447	746	—	—	—	—	586	707	829	1,084
	.030	—	—	—	—	—	—	—	864	—	—	—	—	—	—	—	1,227
Copper Alloys	.0005	0.8	—	—	—	—	—	—	—	25	—	—	—	—	—	—	—
	001	1.5	5	—	—	—	—	—	—	38	76	—	—	—	—	—	—
	.002	2.5	8.7	30	—	—	—	—	—	60	113	223	—	—	—	—	—
	003	3.5	12	42	—	—	—	—	—	79	146	279	—	—	—	—	—
	.004	4 4	15	52	107	—	—	—	—	97	177	331	485	—	—	—	—
	.006	6.1	21	73	148	242	360	499	834	131	235	429	617	798	983	1,184	1,630
	008	—	28	91	186	304	453	629	1,050	—	289	520	740	950	1,165	1,393	1,893
	010	—	31	109	222	364	541	751	1,255	—	341	606	857	1,095	1,337	1,591	2,143
	012	—	—	126	257	421	626	870	1,452	—	—	689	969	1,234	1,502	1,782	2,383
	.015	—	—	151	307	503	749	1,039	1,736	—	—	809	1,131	1,434	1,740	2,056	2,728
	.020	—	—	190	387	633	942	1,308	2,185	—	—	998	1,387	1,750	2,117	2,490	3,275
	.025	—	—	—	—	757	1,127	1,564	2,612	—	—	—	—	2,052	2,475	2,903	3,795
	.030	—	—	—	—	—	—	—	3,023	—	—	—	—	—	—	—	4,293
Leaded Brass	.0005	0.4	—	—	—	—	—	—	—	13	—	—	—	—	—	—	—
	.001	0.7	2.5	—	—	—	—	—	—	19	38	—	—	—	—	—	—
	.002	1.3	4.3	15	—	—	—	—	—	30	56	111	—	—	—	—	—
	003	1.8	6	21	—	—	—	—	—	39	73	139	—	—	—	—	—
	.004	2.2	7.6	26	53	—	—	—	—	49	89	166	243	—	—	—	—
	006	3.1	10	36	74	121	180	250	417	66	118	214	308	399	492	592	815
	.008	—	13	46	93	152	226	314	525	—	145	259	370	475	583	696	947
	010	—	16	55	111	182	271	376	628	—	170	303	428	547	669	796	1,072
	012	—	—	63	128	210	313	435	726	—	—	344	485	616	751	891	1,191
	015	—	—	75	154	252	374	520	868	—	—	404	566	717	870	1,028	1,364
	.020	—	—	95	193	317	471	654	1,093	—	—	499	694	875	1,059	1,245	1,637
	.025	—	—	—	—	378	563	782	1,306	—	—	—	—	1,026	1,238	1,451	1,897
	.030	—	—	—	—	—	—	—	1,511	—	—	—	—	—	—	—	2,147

TABLE 17.4-2 Torque and Thrust Values for Drilling with Split or Crankshaft Point Drills

MATERIAL AND HARDNESS	FEED PER REV.	TORQUE, inch-pounds								THRUST, pounds							
		Drill Diameter, in								Drill Diameter, in							
	in	⅛	¼	½	¾	1	1¼	1½	2	⅛	¼	½	¾	1	1¼	1½	2
Steels 200 Bhn	0.0005	1 3	—	—	—	—	—	—	—	23	—	—	—	—	—	—	—
	001	2 3	7 9	—	—	—	—	—	—	40	71	—	—	—	—	—	—
	002	3 9	14	48	—	—	—	—	—	70	122	216	—	—	—	—	—
	003	5 4	19	66	—	—	—	—	—	96	169	297	—	—	—	—	—
	004	6.9	24	83	173	—	—	—	—	121	212	372	519	—	—	—	—
	006	9.5	33	115	239	401	599	831	1,395	167	292	512	714	905	1,091	1,273	1,630
	.008	—	42	145	300	504	754	1,046	1,756	—	368	643	895	1,133	1,364	1,588	2,028
	.010	—	50	173	359	603	901	1,251	2,099	—	439	768	1,067	1,350	1,623	1,888	2 405
	012	—	—	200	416	698	1,042	1,447	2,429	—	—	887	1,233	1,550	1,872	2,177	2,768
	.015	—	—	239	497	834	1 246	1,730	2,904	—	—	1,060	1,471	1,858	2,230	2,591	3,290
	020	—	—	301	625	1,050	1,569	2,178	3,655	—	—	1,332	1,848	2 333	2.798	3.248	4.116
	.025	—	—	—	—	1,255	1,875	2,603	4,369	—	—	—	—	2,784	3,337	3,872	4,902
	.030	—	—	—	—	—	—	—	5,055	—	—	—	—	—	—	—	5,657
Steels 300 Bhn	0.0005	1.7	—	—	—	—	—	—	—	30	—	—	—	—	—	—	—
	001	2.9	10	—	—	—	—	—	—	52	91	—	—	—	—	—	—
	002	5.1	18	62	—	—	—	—	—	90	158	279	—	—	—	—	—
	.003	7	24	85	—	—	—	—	—	124	218	383	—	—	—	—	—
	.004	9	31	107	223	—	—	—	—	156	273	480	671	—	—	—	—
	.006	12	43	149	308	517	773	1,074	1,802	216	378	662	922	1,169	1,409	1,644	2,106
	008	—	54	187	388	651	973	1,351	2,268	—	475	831	1,156	1,464	1,762	2,052	2,619
	.010	—	64	224	464	779	1,164	1,615	2,711	—	567	992	1,378	1,744	2,096	2,439	2,107
	012	—	—	259	537	901	1,346	1,869	3,137	—	—	1,146	1,592	2,013	2,418	2,811	3,575
	015	—	—	309	642	1,077	1,609	2,235	3,751	—	—	1,369	1,900	2,400	2,881	3,347	4,249
	.020	—	—	389	808	1,356	2,026	2,813	4,721	—	—	1,720	2,387	3,014	3,614	4,195	5,317
	.025	—	—	—	—	1,621	2,422	3,363	5,644	—	—	—	—	3,597	4,311	5,002	6,332
	030	—	—	—	—	—	—	—	6,530	—	—	—	—	—	—	—	7,307
Steels 400 Bhn	0005	1.8	—	—	—	—	—	—	—	33	—	—	—	—	—	—	—
	001	3 2	11	—	—	—	—	—	—	57	100	—	—	—	—	—	—
	002	5.6	19	68	—	—	—	—	—	99	173	306	—	—	—	—	—
	.003	7.7	27	94	—	—	—	—	—	136	239	420	—	—	—	—	—
	.004	9.7	34	118	244	—	—	—	—	172	300	527	736	—	—	—	—
	006	13	47	163	338	568	848	1,178	1,976	237	414	726	1,011	1,283	1,546	1,803	2,310
	008	—	59	205	426	714	1,068	1,482	2,488	—	521	911	1,268	1,606	1,932	2,250	2,873
	.010	—	70	245	509	854	1,276	1,772	2,974	—	622	1,088	1,512	1,913	2,299	2,675	3,407
	.012	—	—	284	589	988	1,477	2,050	3,441	—	—	1,257	1,746	2,208	2,652	3,083	3,921
	015	—	—	339	704	1,181	1,765	2,451	4,113	—	—	1,501	2,084	2,633	3,160	3,671	4,661
	020	—	—	427	886	1,487	2,222	3,085	5,178	—	—	1,887	2,618	3,305	3,964	4,601	5,832
	.025	—	—	—	—	1,778	2,656	3,688	6,190	—	—	—	—	3,945	4,728	5,486	6,945
	.030	—	—	—	—	—	—	—	7,162	—	—	—	—	—	—	—	8,014
Aluminum Alloys	.0005	0.4	—	—	—	—	—	—	—	6.8	—	—	—	—	—	—	—
	.001	0.7	2.3	—	—	—	—	—	—	12	21	—	—	—	—	—	—
	002	1.1	4	14	—	—	—	—	—	20	36	63	—	—	—	—	—
	0u3	1.6	5 5	19	—	—	—	—	—	28	49	87	—	—	—	—	—
	004	2	7	24	50	—	—	—	—	35	62	108	152	—	—	—	—
	.006	2.8	9.6	34	70	117	175	242	407	49	85	149	208	264	318	371	476
	.008	—	12	42	88	147	220	305	512	—	107	188	261	331	398	463	591
	.010	—	14	50	105	176	263	365	612	—	128	224	311	394	473	551	701
	.012	—	—	58	121	203	304	422	708	—	—	259	359	455	546	635	807
	.015	—	—	70	145	243	363	505	847	—	—	309	429	542	651	756	960
	.020	—	—	88	182	306	457	635	1,066	—	—	389	539	681	816	947	1,201
	.025	—	—	—	—	366	547	759	1,274	—	—	—	—	812	973	1,129	1,430
	.030	—	—	—	—	—	—	—	1,475	—	—	—	—	—	—	—	1,650

17.4 Estimating Torque and Thrust in Drilling

TABLE 17.4-2—Continued

MATERIAL AND HARDNESS	FEED PER REV.	TORQUE, inch-pounds								THRUST, pounds							
		Drill Diameter, in								Drill Diameter, in							
	in	⅛	¼	½	¾	1	1¼	1½	2	⅛	¼	½	¾	1	1¼	1½	2
Magnesium Alloys	0005	0 2	—	—	—	—	—	—	—	3 9	—	—	—	—	—	—	—
	001	0.4	1 3	—	—	—	—	—	—	6 7	12	—	—	—	—	—	—
	002	0.7	2 3	8	—	—	—	—	—	12	20	36	—	—	—	—	—
	003	0.9	3 2	11	—	—	—	—	—	16	28	49	—	—	—	—	—
	004	1 1	4	14	29	—	—	—	—	20	35	62	87	—	—	—	—
	006	1.6	5 5	19	40	67	100	138	232	28	49	85	119	151	182	212	272
	008	—	6 9	24	50	84	126	174	293	—	61	107	149	189	227	265	338
	010	—	8 3	29	60	100	150	208	350	—	73	128	178	225	270	315	401
	012	—	—	33	69	116	174	241	405	—	—	148	205	260	312	363	461
	.015	—	—	40	83	139	208	288	484	—	—	177	245	310	372	432	548
	020	—	—	50	104	175	261	363	609	—	—	222	308	389	466	541	686
	025	—	—	—	—	209	312	434	728	—	—	—	—	464	556	645	817
	030	—	—	—	—	—	—	—	843	—	—	—	—	—	—	—	943
Copper Alloys	0005	0 8	—	—	—	—	—	—	—	14	—	—	—	—	—	—	—
	001	1.3	4 6	—	—	—	—	—	—	23	41	—	—	—	—	—	
	002	2.3	8	28	—	—	—	—	—	41	71	126	—	—	—	—	—
	003	3 2	11	39	—	—	—	—	—	56	98	173	—	—	—	—	—
	004	4	14	49	101	—	—	—	—	71	123	217	303	—	—	—	—
	006	5.5	19	67	139	234	349	485	814	98	171	299	416	528	637	743	951
	008	—	24	84	175	294	440	610	1,024	—	214	275	522	661	796	927	1,183
	010	—	29	101	209	352	525	730	1,225	—	256	448	622	788	947	1,102	1,403
	.012	—	—	117	242	407	608	844	1,417	—	—	518	719	909	1,093	1,270	1,614
	015	—	—	140	290	486	727	1,005	1,694	—	—	618	858	1,089	1,301	1,512	1,919
	.020	—	—	176	365	612	915	1,270	2,132	—	—	777	1,078	1,361	1,632	1,895	2,401
	.025	—	—	—	—	732	1,094	1,519	2,549	—	—	—	—	1,624	1,947	2,259	2,860
	030	—	—	—	—	—	—	—	2,949	—	—	—	—	—	—	—	3,330
Leaded Brass	.0005	0.4	—	—	—	—	—	—	—	6.8	—	—	—	—	—	—	—
	001	0.7	2 3	—	—	—	—	—	—	12	21	—	—	—	—	—	—
	002	1 1	4	14	—	—	—	—	—	20	36	63	—	—	—	—	—
	003	1.6	5	19	—	—	—	—	—	28	49	87	—	—	—	—	—
	.004	2	7	24	50	—	—	—	—	35	62	108	152	—	—	—	—
	.006	2.8	9.6	34	70	117	175	242	407	50	85	149	208	264	318	371	476
	008	—	12	42	88	147	220	305	512	—	107	188	261	331	398	463	591
	010	—	14	50	105	176	263	365	612	—	128	224	311	394	473	551	701
	012	—	—	58	121	203	304	422	708	—	—	259	359	455	546	635	807
	015	—	—	70	145	243	363	505	847	—	—	309	429	542	651	756	960
	020	—	—	88	182	306	457	635	1,066	—	—	389	539	681	816	947	1,201
	.025	—	—	—	—	366	547	759	1,274	—	—	—	—	812	973	1,129	1,430
	.030	—	—	—	—	—	—	—	1,475	—	—	—	—	—	—	—	1,650

TABLE 17.4-3 Torque and Thrust Values for Drilling with Metric Standard Point Drills

MATERIAL AND HARDNESS	FEED PER REV.	TORQUE, newton-meters								THRUST, newtons							
		Drill Diameter, mm								Drill Diameter, mm							
	mm	3	6	12	18	25	30	35	50	3	6	12	18	25	30	35	50
Steels 200 Bhn	.013	0.16	—	—	—	—	—	—	—	196	—	—	—	—	—	—	—
	.025	0.28	0.96	—	—	—	—	—	—	289	578	—	—	—	—	—	—
	.050	0.50	1.70	5.88	—	—	—	—	—	454	863	1,700	—	—	—	—	—
	.075	0.68	2.37	8.02	—	—	—	—	—	602	1,139	2,126	—	—	—	—	—
	.102	0.90	2.94	10.17	20.68	—	—	—	—	7,406	1,352	2,527	3,700	—	—	—	—
	.15	1.24	4.07	14.00	28.59	47	70	97	162	1,000	1,793	3,270	4,706	6,085	7,504	9,030	12,437
	.20	—	5.08	17.6	36	59	88	122	203	—	2,206	3,963	5,636	7,246	8,883	10,622	14,439
	.25	—	6.10	21	43	70	105	146	243	—	2,598	4,622	6,534	8,345	10,195	12,135	16,343
	.36	—	—	24	50	81	121	168	281	—	—	5,258	7,393	9,408	11,454	13,585	18,171
	.40	—	—	29	60	97	145	201	336	—	—	6,170	8,625	10,934	13,271	15,676	20,804
	.50	—	—	37	75	123	182	253	423	—	—	7,613	10,578	13,349	16,143	18,989	24,972
	.65	—	—	—	—	147	218	303	506	—	—	—	—	15,644	18,876	21,692	28,936
	.75	—	—	—	—	—	—	—	653	—	—	—	—	—	—	—	32,739
Steels 300 Bhn	.013	0.21	—	—	—	—	—	—	—	249	—	—	—	—	—	—	—
	.025	0.36	1.24	—	—	—	—	—	—	374	750	—	—	—	—	—	—
	.050	0.63	2.15	7.57	—	—	—	—	—	587	1,117	2,197	—	—	—	—	—
	.075	0.88	3.05	10.4	—	—	—	—	—	778	1,441	2,749	—	—	—	—	—
	.102	1.01	3.73	13.1	26.7	—	—	—	—	946	1,303	3,263	4,782	—	—	—	—
	.15	1.53	5.20	18.1	36.9	60.4	89.9	125	208	1,290	2,318	4,226	6,081	7,860	9,693	11,663	16,063
	.20	—	6.55	22.8	46.4	76.0	113	157	263	—	2,847	5,120	7,291	9,359	11,476	13,718	18,651
	.25	—	7.90	27.2	55.6	91	135	188	314	—	3,354	5,970	8,443	10,782	13,171	15,671	21,107
	.36	—	—	31.5	64.3	105	157	217	363	—	—	6,788	9,546	12,153	14,800	17,548	23,469
	.40	—	—	37.7	76.8	126	187	299	434	—	—	7,967	11,138	14,123	17,143	20,248	26,872
	.50	—	—	47.5	96.7	158	236	327	547	—	—	9,835	13,660	17,241	20,853	24,527	32,254
	.65	—	—	—	—	189	282	391	654	—	—	—	—	20,208	24,380	28,593	37,374
	.75	—	—	—	—	—	—	—	756	—	—	—	—	—	—	—	42,289
Steels 400 Bhn	.013	0.23	—	—	—	—	—	—	—	276	—	—	—	—	—	—	—
	.025	0.40	1.36	—	—	—	—	—	—	409	823	—	—	—	—	—	—
	.050	0.70	2.37	8.24	—	—	—	—	—	643	1,219	2,411	—	—	—	—	—
	.075	0.96	3.28	11.4	—	—	—	—	—	854	1,579	3,016	—	—	—	—	—
	.102	1.24	4.18	14.4	29.3	—	—	—	—	1,050	1,918	3,581	5,215	—	—	—	—
	.15	1.69	5.76	19.9	40.4	66.2	98.7	137	229	1,415	2,540	4,630	6,668	8,630	10,631	12,793	17,619
	.20	—	7.23	25.1	50.9	83.5	124	173	288	—	3,123	5,614	7,993	10,262	12,584	15,048	20,453
	.25	—	8.58	29.9	60.9	99.8	148	206	344	—	3,679	6,548	9,257	11,828	14,443	17,188	23,149
	.36	—	—	34.6	70.5	115	172	239	398	—	—	7,446	10,471	13,327	16,227	19,247	25,742
	.40	—	—	41.3	84.2	138	205	285	476	—	—	8,741	12,219	15,489	18,803	22,210	29,469
	.50	—	—	52.0	106	174	259	359	600	—	—	10,787	14,982	18,910	22,873	26,898	35,377
	.65	—	—	—	—	208	309	429	717	—	—	—	—	22,161	26,743	31,360	40,990
	.75	—	—	—	—	—	—	—	829	—	—	—	—	—	—	—	46,395
Aluminum Alloys	.013	0.05	—	—	—	—	—	—	—	57.8	—	—	—	—	—	—	—
	.025	0.08	0.28	—	—	—	—	—	—	84.5	169	—	—	—	—	—	—
	.050	0.15	0.49	1.69	—	—	—	—	—	133	251	494	—	—	—	—	—
	.075	0.20	0.68	2.37	—	—	—	—	—	173	325	618	—	—	—	—	—
	.102	0.25	0.86	2.94	5.99	—	—	—	—	218	396	738	1,080	—	—	—	—
	.15	0.35	1.19	4.07	8.36	13.7	20.3	28.2	47.0	294	525	952	1,370	1,775	2,188	2,633	3,625
	.20	—	1.47	5.20	10.5	17.2	25.5	35.5	59.3	—	645	1,157	1,646	2,113	2,593	3,096	4,212
	.25	—	1.81	6.21	12.5	20.6	30.6	42.5	71	—	756	1,348	1,904	2,433	2,976	3,541	4,768
	.36	—	—	7.11	14.5	23.7	35.4	49.1	82	—	—	1,535	2,157	2,745	3,341	3,963	5,298
	.40	—	—	8.47	17.4	28.3	42.2	58.8	98	—	—	1,797	2,518	3,189	3,870	4,573	6,097
	.50	—	—	10.7	21.8	35.8	53.2	73.9	124	—	—	2,220	3,087	3,892	4,710	5,538	7,282
	.65	—	—	—	—	42.7	63.6	88.4	148	—	—	—	—	4,564	5,507	6,454	8,438
	.75	—	—	—	—	—	—	—	171	—	—	—	—	—	—	—	9,550

17.4 Estimating Torque and Thrust in Drilling

TABLE 17.4-3—Continued

MATERIAL AND HARDNESS	FEED PER REV.	TORQUE, newton-meters								THRUST, newtons							
		Drill Diameter, mm								Drill Diameter, mm							
	mm	3	6	12	18	25	30	35	50	3	6	12	18	25	30	35	50
Magnesium Alloys	.013	0.023	—	—	—	—	—	—	—	32	—	—	—	—	—	—	—
	.025	0.045	0.158	—	—	—	—	—	—	49	98	—	—	—	—	—	—
	.050	0.079	0.282	0.971	—	—	—	—	—	75	142	285	—	—	—	—	—
	.075	0.113	0.384	1.34	—	—	—	—	—	102	187	356	—	—	—	—	—
	.102	0.147	0.486	1.69	3.45	—	—	—	—	125	227	423	618	—	—	—	—
	.15	0.192	0.678	2.37	4.75	7.20	11.64	16.16	26.9	147	262	485	703	912	1,130	1,366	1,900
	.20	—	0.874	2.94	5.99	9.83	14.6	20.3	33.9	—	369	658	939	1,210	1,481	1,770	2,406
	.25	—	1.02	3.50	7.23	11.8	17.5	24.3	40	—	431	770	1,090	1,392	1,700	2,024	2,722
	.36	—	—	4.07	8.25	13.6	20.2	28.2	46.9	—	—	876	1,232	1,568	1,906	2,264	3,029
	.40	—	—	4.86	10.1	16.3	24.2	33.6	56	—	—	1,028	1,437	1,824	2,210	2,610	3,470
	50	—	—	6.10	12.4	20.5	30.4	42.3	70.5	—	—	1,268	1,761	2,224	2,691	3,163	4,164
	.65	—	—	—	—	24.4	36.4	50.5	84.3	—	—	—	—	2,607	3,145	3,688	4,822
	.75	—	—	—	—	—	—	—	97.6	—	—	—	—	—	—	—	5,458
Copper Alloys	.013	0.090	—	—	—	—	—	—	—	113	—	—	—	—	—	—	—
	.025	0.169	0.565	—	—	—	—	—	—	169	338	—	—	—	—	—	—
	.050	0.282	0.983	3.39	—	—	—	—	—	267	503	992	—	—	—	—	—
	.075	0.395	1.36	4.75	—	—	—	—	—	351	649	1,241	—	—	—	—	—
	.102	0.497	1.71	5.88	12.1	—	—	—	—	431	787	1,472	2,157	—	—	—	—
	.15	0.689	2.37	8.25	16.7	27.3	40.6	56.4	94.2	583	1,045	1,908	2,745	3,550	4,373	5,267	7,250
	.20	—	2.94	10.3	21	34.3	51.2	71.1	119	—	1,286	2,313	3,292	4,226	5,182	6,196	8,420
	.25	—	3.50	12.3	25	41	61.1	84.9	142	—	1,517	2,696	3,812	4,870	5,947	7,077	9,533
	.36	—	—	14.2	29	47.6	70.7	98.3	164	—	—	3,065	4,310	5,489	6,681	7,927	10,600
	.40	—	—	17.1	34.7	56.8	84.6	117	196	—	—	3,600	5,030	6,379	7,740	9,146	12,135
	.50	—	—	21.5	43.7	71.5	106	148	247	—	—	4,439	6,170	7,784	9,417	11,076	14,568
	.65	—	—	—	—	85.5	127	177	295	—	—	—	—	9,128	11,009	12,913	16,881
	.75	—	—	—	—	—	—	—	342	—	—	—	—	—	—	—	19,096
Leaded Brass	.013	0.045	—	—	—	—	—	—	—	56.5	—	—	—	—	—	—	—
	.025	0.079	0.282	—	—	—	—	—	—	84.5	169	—	—	—	—	—	—
	.050	0.147	0.486	1.69	—	—	—	—	—	133	251	494	—	—	—	—	—
	.075	0.203	0.678	2.37	—	—	—	—	—	173	325	618	—	—	—	—	—
	.102	0.249	0.859	2.94	5.99	—	—	—	—	218	396	738	1,081	—	—	—	—
	.15	0.350	1.19	4.07	8.36	13.7	20.3	28.2	47	294	525	952	1,370	1,775	2,188	2,633	3,625
	.20	—	1.47	5.20	10.5	17.2	25.5	35.5	59.3	—	645	1,152	1,646	2,113	2,593	3,096	4,212
	.25	—	1.81	6.21	12.5	20.6	30.6	42.5	70.9	—	756	1,348	1,904	2,433	2,976	3,541	4,768
	.36	—	—	7.11	14.5	23.7	35.4	49	82	—	—	1,530	2,157	2,740	3,340	3,963	5,298
	.40	—	—	8.47	17.4	28.5	42.3	58.8	98	—	—	1,797	2,518	3,189	3,870	4,573	6,067
	.50	—	—	10.7	21.8	35.8	53.2	73.9	123	—	—	2,220	3,087	3,892	4,710	5,538	7,282
	.65	—	—	—	—	42.7	63.6	88.3	147	—	—	—	—	4,564	5,507	6,454	8,438
	.75	—	—	—	—	—	—	—	171	—	—	—	—	—	—	—	9,550

TABLE 17.4-4 Torque and Thrust Values for Drilling with Metric Split or Crankshaft Point Drills

MATERIAL AND HARDNESS	FEED PER REV.	TORQUE, newton meters								THRUST, newtons							
		Drill Diameter, mm								Drill Diameter, mm							
	mm	3	6	12	18	25	30	35	50	3	6	12	18	25	30	35	50
Steels 200 Bhn	.013	0.15	—	—	—	—	—	—	—	102	—	—	—	—	—	—	—
	.025	0.26	0.89	—	—	—	—	—	—	178	316	—	—	—	—	—	—
	.050	0.44	1.58	5.42	—	—	—	—	—	311	543	961	—	—	—	—	—
	.075	0.61	2.15	7.46	—	—	—	—	—	427	752	1,321	—	—	—	—	—
	.102	0.78	2.71	9.38	20	—	—	—	—	536	943	1,655	2,309	—	—	—	—
	.15	1.07	3.73	13	27	45	66	94	158	743	1,300	2,277	3,176	4,026	4,853	5,663	7,250
	.20	—	4.75	16.4	34	57	85	118	198	—	1,637	2,860	3,981	5,040	6,067	7,064	9,021
	.25	—	5.64	19.5	41	68	102	141	237	—	1,953	3,416	4,746	6,005	7,219	8,398	10,698
	.38	—	—	22.5	47	79	118	163	274	—	—	3,946	5,485	6,930	8,327	9,684	12,313
	.40	—	—	27	56	94	141	195	328	—	—	4,715	6,543	8,265	9,920	11,525	14,635
	.50	—	—	34	71	119	177	246	413	—	—	5,925	8,220	10,378	12,446	14,446	18,309
	.65	—	—	—	—	142	212	294	494	—	—	—	—	12,384	14,844	17,224	21,805
	.75	—	—	—	—	—	—	—	571	—	—	—	—	—	—	—	25,164
Steels 300 Bhn	.013	0.19	—	—	—	—	—	—	—	133	—	—	—	—	—	—	—
	.025	0.33	1.13	—	—	—	—	—	—	231	405	—	—	—	—	—	—
	.050	0.58	2.03	7	—	—	—	—	—	400	703	1,241	—	—	—	—	—
	.075	0.79	2.71	9.6	—	—	—	—	—	552	970	1,704	—	—	—	—	—
	.102	1.01	3.50	12.1	25.2	—	—	—	—	694	1,214	2,135	2,965	—	—	—	—
	.15	1.36	4.86	16.8	34.8	58.4	87.3	121	204	961	1,681	2,945	4,100	5,200	6,268	7,313	9,368
	.20	—	6.10	21.1	43.8	73.6	110	153	256	—	2,113	3,696	5,142	6,512	7,838	9,128	11,650
	.25	—	7.23	25.3	52.4	88	132	182	306	—	2,522	4,413	6,130	7,758	9,323	10,849	13,820
	.38	—	—	29.2	60.6	102	152	211	354	—	—	5,098	7,082	8,954	10,756	12,504	15,902
	.40	—	—	34.9	72.5	122	182	253	424	—	—	6,090	8,452	10,676	12,815	14,888	18,900
	.50	—	—	44	91.3	153	229	318	533	—	—	7,650	10,618	13,407	16,076	18,660	23,651
	.65	—	—	—	—	183	274	380	638	—	—	—	—	16,000	19,176	22,250	28,166
	.75	—	—	—	—	—	—	—	738	—	—	—	—	—	—	—	32,503
Steels 400 Bhn	.013	0.20	—	—	—	—	—	—	—	147	—	—	—	—	—	—	—
	.025	0.36	1.24	—	—	—	—	—	—	254	445	—	—	—	—	—	—
	.050	0.63	2.15	7.66	—	—	—	—	—	440	770	1,361	—	—	—	—	—
	.075	0.87	3.05	10.6	—	—	—	—	—	605	1,063	1,868	—	—	—	—	—
	.102	1.10	3.84	13.3	27.6	—	—	—	—	765	1,334	2,344	3,274	—	—	—	—
	.15	1.47	5.31	18.4	38.2	64.2	95.8	133	223	1,054	1,842	3,229	4,497	5,707	6,877	8,020	10,275
	.20	—	6.66	23.2	48.1	80.7	121	167	281	—	2,318	4,052	5,640	7,144	8,594	10,008	12,780
	.25	—	7.91	27.7	57.5	96.5	144	200	336	—	2,767	4,840	6,726	8,510	10,226	11,900	15,155
	.38	—	—	32.0	66.5	112	167	232	389	—	—	5,591	7,767	9,822	11,797	13,714	17,441
	.40	—	—	38.3	79.5	133	199	277	465	—	—	6,677	9,270	11,712	14,056	16,329	20,733
	.50	—	—	48.2	100	168	251	349	585	—	—	8,394	11,645	14,700	17,633	20,466	25,942
	.65	—	—	—	—	200	300	417	700	—	—	—	—	17,548	21,031	24,403	30,893
	.75	—	—	—	—	—	—	—	810	—	—	—	—	—	—	—	35,648
Aluminum Alloys	.013	0.05	—	—	—	—	—	—	—	30.2	—	—	—	—	—	—	—
	.025	0.08	0.26	—	—	—	—	—	—	53.4	93.4	—	—	—	—	—	—
	.050	0.12	0.45	1.58	—	—	—	—	—	88.9	160	280	—	—	—	—	—
	.075	0.18	0.62	2.15	—	—	—	—	—	125	218	387	—	—	—	—	—
	.102	0.23	0.79	2.71	5.66	—	—	—	—	156	276	480	676	—	—	—	—
	.15	0.36	1.06	3.84	7.91	13.2	19.8	27.4	46.0	218	378	663	925	1,174	1,415	1,650	2,117
	.20	—	1.36	4.75	9.9	16.8	24.8	34.5	57.8	—	476	836	1,161	1,472	1,770	2,060	2,629
	.25	—	1.58	5.65	11.9	19.9	29.7	41.2	69.1	—	569	996	1,383	1,753	2,104	2,451	3,118
	.38	—	—	6.55	13.7	22.9	34.3	47.7	80.0	—	—	1,152	1,597	2,024	2,429	2,825	3,590
	.40	—	—	7.90	16.4	27.5	41.0	57.1	95.7	—	—	1,375	1,906	2,410	2,896	3,363	4,270
	.50	—	—	9.94	20.6	34.6	51.6	71.7	120	—	—	1,730	2,398	3,029	3,630	4,212	5,342
	.65	—	—	—	—	41.4	61.8	85.8	144	—	—	—	—	3,812	4,337	5,022	6,360
	.75	—	—	—	—	—	—	—	167	—	—	—	—	—	—	—	7,340

TABLE 17.4-4 –Continued

MATERIAL AND HARDNESS	FEED PER REV	TORQUE, newton-meters								THRUST, newtons							
		Drill Diameter, mm								Drill Diameter, mm							
	mm	3	6	12	18	25	30	35	50	3	6	12	18	25	30	35	50
Magnesium Alloys	013	0.023	—	—	—	—	—	—	—	17.8	—	—	—	—	—	—	—
	025	0.045	0.147	—	—	—	—	—	—	29.6	53.4	—	—	—	—	—	—
	050	0.079	0.260	0.903	—	—	—	—	—	53.3	88.9	160	—	—	—	—	—
	075	0.102	0.362	1.24	—	—	—	—	—	71.1	125	218	—	—	—	—	—
	102	0.124	0.452	1.58	3.28	—	—	—	—	89	156	276	387	—	—	—	—
	15	0.181	0.621	2.15	4.52	7.67	11.5	15.6	26.2	125	218	378	529	672	809	943	1,210
	20	—	0.780	2.71	5.65	9.49	14.2	19.7	33.1	—	271	476	663	841	1,010	1,179	1,503
	25	—	0.938	3.26	6.78	11.3	16.9	23.6	39.5	—	325	569	792	1,000	1,200	1,400	1,784
	30	—	—	3.73	7.80	13.1	19.7	27.2	45.8	—	—	656	912	1,157	1,388	1,615	2,060
	40	—	—	4.52	9.38	15.7	23.5	32.6	54.7	—	—	787	1,090	1,379	1,655	1,922	2,436
	50	—	—	5.65	11.8	19.8	29.5	41	68.5	—	—	988	1,370	1,730	2,073	2,406	3,051
	65	—	—	—	—	25.6	38.3	49	82.3	—	—	—	—	2,064	2,473	2,869	3,634
	75	—	—	—	—	—	—	—	96.2	—	—	—	—	—	—	—	4,196
Copper Alloys	013	0.090	—	—	—	—	—	—	—	62	—	—	—	—	—	—	—
	025	0.147	0.620	—	—	—	—	—	—	102	182	—	—	—	—	—	—
	050	0.260	0.904	3.16	—	—	—	—	—	182	316	560	—	—	—	—	—
	075	0.362	1.24	4.41	—	—	—	—	—	249	436	770	—	—	—	—	—
	102	0.451	1.58	5.64	11.4	—	—	—	—	315	547	965	1,348	—	—	—	—
	15	0.621	2.15	7.67	15.7	26.4	39.4	54.8	92.0	436	761	1,330	1,850	2,349	2,834	3,305	4,230
	20	—	2.71	9.49	19.8	32.2	49.7	68.9	116	—	952	1,223	2,321	2,940	3,541	4,124	5,262
	25	—	3.26	11.4	23.6	39.8	59.3	82.5	138	—	1,139	1,993	2,767	3,505	4,212	4,902	6,240
	30	—	—	13.2	27.3	46	68.7	95.4	160	—	—	2,304	3,198	4,043	4,862	5,649	7,160
	40	—	—	15.8	32.8	54.9	82.1	114	191	—	—	2,749	3,817	4,844	5,787	6,726	8,530
	50	—	—	19.9	41.2	69.1	103	143	241	—	—	3,456	4,795	6,054	7,259	8,429	10,680
	65	—	—	—	—	82.7	124	172	288	—	—	—	—	7,224	8,636	10,049	12,722
	75	—	—	—	—	—	—	—	333	—	—	—	—	—	—	—	14,679
Leaded Brass	013	0.045	—	—	—	—	—	—	—	30.2	—	—	—	—	—	—	—
	025	0.079	0.260	—	—	—	—	—	—	53.4	93.4	—	—	—	—	—	—
	050	0.124	0.452	1.58	—	—	—	—	—	89.0	160	280	—	—	—	—	—
	075	0.181	0.621	2.15	—	—	—	—	—	125	218	387	—	—	—	—	—
	102	0.226	0.791	2.71	5.65	—	—	—	—	156	276	480	676	—	—	—	—
	15	0.316	1.08	3.84	7.91	13.2	19.8	27.3	46.0	222	378	663	925	1,174	1,415	1,650	2,117
	20	—	1.36	4.75	9.94	16.6	24.9	34.5	57.8	—	476	836	1,161	1,472	1,770	2,060	2,629
	25	—	1.58	5.65	11.9	19.9	29.7	41.2	69.0	—	569	996	1,383	1,753	2,104	2,450	3,118
	36	—	—	6.55	13.7	22.9	34.3	47.7	80.0	—	—	1,152	1,597	2,024	2,429	2,825	3,590
	40	—	—	7.90	16.4	27.5	41.0	57.0	95.7	—	—	1,375	1,906	2,410	2,896	3,363	4,270
	50	—	—	9.94	20.6	34.6	51.6	71.7	120	—	—	1,730	2,396	3,029	3,629	4,212	5,342
	65	—	—	—	—	41.3	61.8	86.8	144	—	—	—	—	3,812	4,328	5,022	6,360
	75	—	—	—	—	—	—	—	167	—	—	—	—	—	—	—	7,340

SECTION 18

SURFACE TECHNOLOGY

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One of the principal design considerations for highly stressed components should be the surface condition produced during manufacturing. This consideration must include a thorough review of the surface alterations resulting from specific machining operations. Surface technology is the activity that describes, details, and evaluates the condition of both the surface and the surface layers of manufactured components. The historical emphasis on surface texture (roughness, waviness, and lay) has been extended to include the assessment of effects just below the surface, that is, surface integrity, thereby including the influence of the outermost boundary of a component as well as those outermost layers which differ measurably from the base material.

TRENDS AND CONCERNS

In recent years, the demand for increased safety, reliability, and service life has caused considerable attention to be directed to the pronounced influence of the types of surface conditions produced by various manufacturing methods on the resulting properties and performance of components once in service. New and unusual service requirements and conservation of energy and/or materials have brought about the use of thinner sections of improved (and more difficult to fabricate) materials and the introduction of design criteria that employ these materials much closer to their full potential. While part drawings continue to call out configuration, dimensions, tolerances and material properties, surface quality specifications must be added to complete the component definition. All the design elements noted above are intimately interrelated and directly affect component cost and producibility.

The manufacturer, recognizing the above design trends and characteristics, also must be concerned with the attainment of accuracy in thinner parts where distortion from processing stresses is a frequent result. Some of the newer and higher performance alloys used in the thinner and lighter parts also are likely to be altered or more sensitive to thermal gradients or the heat generated by some processes. The emphasis on quality assurance and product reliability increases the importance of recognizing the impact that manufacturing processes may have on material properties. As always, in addition to these concerns and trends the fabrication of a product or component must be accomplished within the constraints of both economics and environmental effects.

RELATIONSHIP OF SURFACE TEXTURE AND SURFACE INTEGRITY

Traditionally, surface texture (roughness, waviness and lay) has been accepted as the criterion which controls the quality of a surface. Direct relationships are widely assumed to exist between surface roughness and fatigue strength as well as other properties. Ample data have now been accumulated to indicate that surface texture is only part of the consideration. Metallurgical and other alterations below the surface also have a major influence on material performance. This becomes particularly important where high stresses or severe environments are encountered by the workpiece.

While most alterations occur in the first 0.015 inch (0.38 mm) below the surface, this distance can be a significant part of the total thickness of the thinner parts being designed. In addition, it should be noted that many component failures have originated within the first few thousandths inch below the geometrical surface. These facts alone support the need for design, manufacturing, and quality assurance engineers to exhibit interest in and understanding of both aspects of surface technology—surface texture and surface integrity—in order to produce safe, reliable and long life components.

The influence of manufactured surfaces on component properties has been investigated most extensively for the material removal processes. Figure 18.1-1 shows the surface technology effects studied to date. During machining, process energies blend with work material properties to produce a wide variety of these surface effects. Surface effects produced during the machining process affect the properties of the work material and in turn of the component reliability, as shown in figure 18.1-2. Studies have demonstrated that each material removal process has its own effect on each work material. It has also been shown that for each process the intensity or energy level may have a distinctive effect on the specific metallurgical state of the work material.

ECONOMICS

The cost of producing a machined component increases as surface specifications increase. Sophisticated and extensive surface texture or surface integrity requirements are justified only if they are necessary for the component part to fulfill its function. Many parts require only a roughing operation to attain their desired shape and tolerance. Finishing operations may improve quality but they add cost, and while emphasis on surface integrity considerations increases component reliability, cost also may increase. To eliminate unnecessary costs it is important to apply texture and integrity specifications selectively to only those areas of a part where they are needed, rather than to impose these requirements across the entire surface of the part. The relationship between surface texture and machining costs is discussed further in section 21.

The application of surface integrity principles and guidelines can increase the number of good parts produced or, conversely, reduce manufacturing losses. Surface integrity evaluations should consider the entire part processing sequence and emphasize the achievement of high quality in the "as shipped" surface produced. The price for inattention to surface integrity can be premature component failure or loss of reliability.

QUALITY ASSURANCE

Surface technology ranks with dimensional configuration and tolerance as visual evidence of quality. Deterioration of surface quality with time or with number of parts produced is a handy clue to deteriorating tools or process settings. A 10-percent rule of thumb has been found to be a practical limit within which normal manufacturing operations can be conducted without jeopardizing surface qual-

ity. This rule states that if surface roughness increases by 10 percent (in microinches R_a or rms) or if any one of the operating parameters has been reset or "adjusted" by plus or minus 10 percent from the planned values, immediate questions should be raised as to the control status of the process. If two or more parameters are "adjusted" by 10 percent or more, the process is no longer controlled and should be shut down until corrective action is effective.

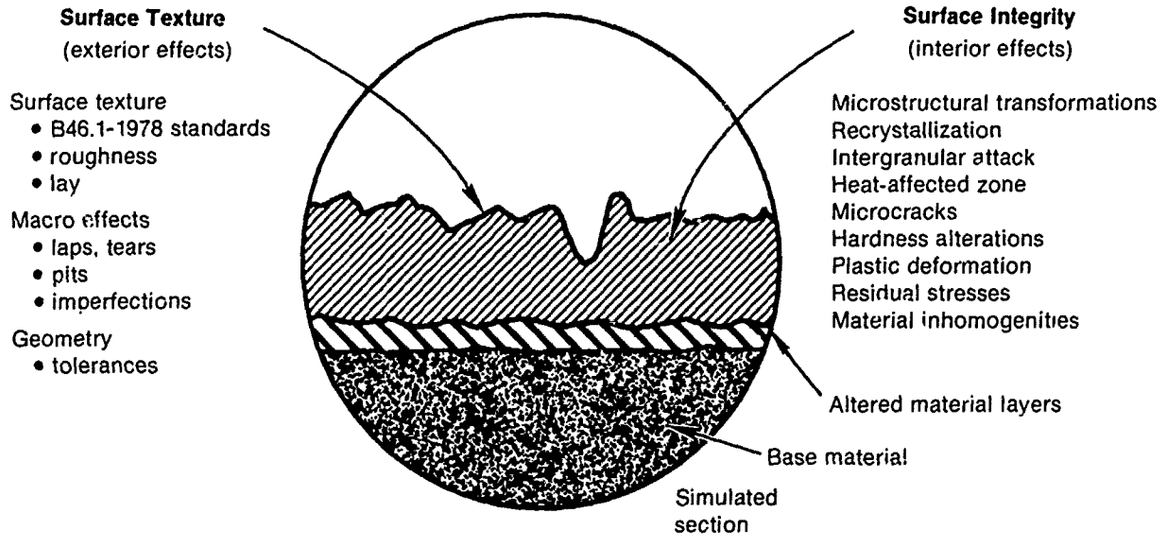


Figure 18.1–1 Surface technology effects.

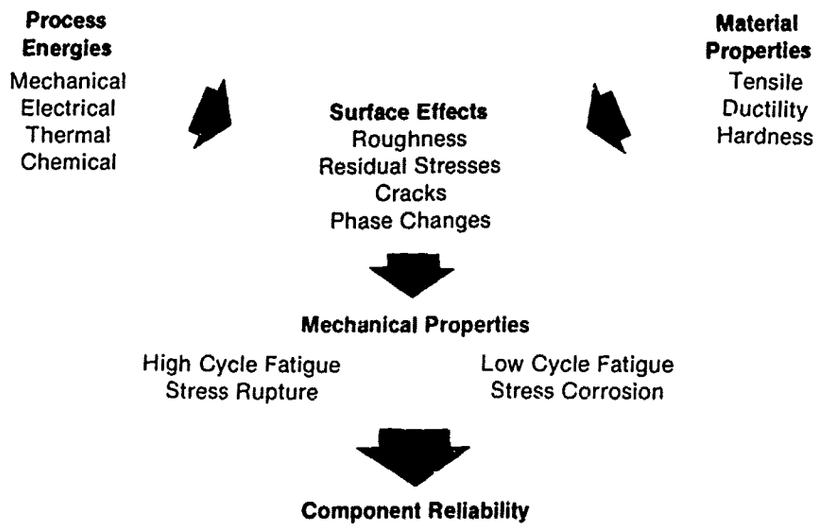


Figure 18.1–2 Interaction of processes with materials.

INTRODUCTION

The surfaces produced by machining generally are irregular and complex. Despite this, the majority of machined parts can satisfactorily perform their functions with general, uncomplicated surface texture specifications. Many machining processes can meet these general surface texture requirements with ordinary process control and a minimum of quality control. Dimensional checks and visual examination for macro imperfections usually are sufficient. When surface roughness requirements exceed about 63 microinches R_a (1.6 μm) most companies will use a visual check rather than a measurement of the roughness profile. Often the visual check is aided by using sets of sample roughness specimens. Any more exacting specifications for most surfaces would serve no practical purpose and would result in needless expense.

Parts that are highly engineered, heavily stressed or subjected to unusual environments usually have more specific and detailed surface quality requirements. Tolerance requirements for these parts may also need to be closely allied to the roughness allowed. For some of these parts, history or testing has demonstrated a direct relationship between performance and surface texture. Quality control to measure surface texture is, therefore, necessary for these parts. The following are examples of parts that require enhanced surface texture specifications in order to improve fatigue strength, corrosion resistance, cleanliness, appearance, coatability, sealing or product performance:

1. Antifriction bearings and airfoils
2. Objects operating in corrosive environments
3. Food preparation devices
4. Telescope lense, plug gages and rolling mill rolls
5. Journal bearings
6. Painted or coated surfaces
7. Sealing surfaces or friction clamped assemblies

Parts that are critically stressed, product-life-limiting or safety controlling, or those specific areas on such parts, should have additional specifications that include surface integrity considerations, as described in section 18.3.

SURFACE TEXTURE DEFINED

Surface texture is the repetitive or random deviations from the nominal surface which form the three-dimensional surface topography. A variety of mechanical, electronic and optical devices are available to measure these deviations by sampling the profile of the workpiece. Figure 18.2-1 shows a comparison between the measured and the nominal profiles for a given surface.

American National Standard ANSI B46.1-1978 describes, standardizes and calls out acceptable measuring instrumentation for surface texture.[1] (Internationally, ISO R468 compares in content.) According to the standard, surface texture includes four elements—roughness, waviness, lay and flaws. Figure 18.2-2 shows these characteristics in relation to a unidirectional lay surface.

[1]ANSI B46.1-1978, "Surface Texture" (which includes ANSI Y14.36-1978 "Surface Texture Symbols") should be available to and be read by everyone concerned with specifying or measuring surface texture. Copies are available from the American Society of Mechanical Engineers, United Engineering Center, 345 East 47th Street, New York, NY 10017.

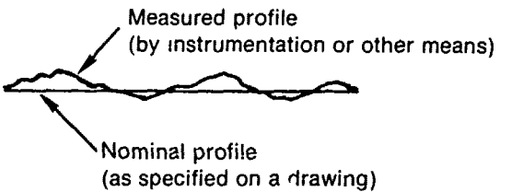


Figure 18.2-1 Surface texture profile. (Based on ANSI B46.1-1978)

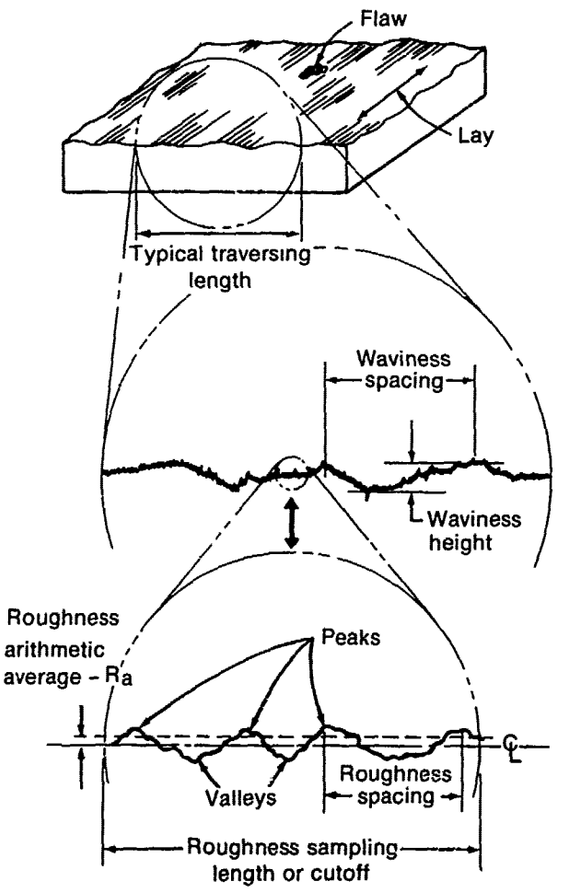


Figure 18.2-2 Pictorial display of unidirectional lay surface characteristics. (Based on ANSI B46.1-1978)

18.2 Surface Texture

Definitions for the four elements of surface texture are as follows:

Roughness consists of the finer irregularities which generally result from the inherent action of the production process. These include transverse feed marks and other irregularities within the limits of the sampling length.

Waviness includes all irregularities whose spacing is greater than the roughness sampling length and less than the waviness sampling length. Waviness may result from machine or work deflections, chatter, vibration, heat treatment or cutting tool runout. Roughness may be considered superimposed on a "wavy" surface.

Lay is the direction of the predominant surface pattern, ordinarily determined by the production method used.

Flaws are unintentional irregularities which occur at one place or at relatively infrequent or widely varying intervals on the surface. Flaws include cracks, blow holes, inclusions, checks, ridges, scratches, etc. Unless otherwise specified, the effect of flaws shall not be included in the roughness average measurements. Where flaws are to be restricted or controlled, a special note as to the method of inspection should be included on the drawing or in the specifications.

Surface finish is a colloquial term widely used to denote the general quality of a surface. Surface finish is not specifically tied to the texture or characteristic pattern of the surface, nor is it tied to specific roughness values; however, a "good" finish implies low roughness values and vice versa. The term surface finish is not as precisely defined as are the terminologies used in the American National Standard, nor is it necessarily expressed numerically.

SURFACE TEXTURE SYMBOLS

The description and specification of surface texture is accomplished by means of symbols and conventions as presented in the ANSI Standard Y14.36-1978 (almost in complete agreement with ISO 1302). The symbol used to designate surface roughness is the check mark with a horizontal extension as shown in figure 18.2-3. Roughness, which is the most commonly used surface parameter, is specified by placing the height rating in microinches (one microinch = 0.000001 inch) or micrometers (one micrometer = 0.000001 meter) to the left of the check mark. If there is a maximum and a minimum rating, the two numbers are placed one above the other. Roughness is defined as the arithmetic average (AA) deviation of the surface expressed in microinches from a mean line or centerline (see figures 18.2-2 and 18.2-4). R_a is a symbol for roughness that has been adopted internationally. Surface roughness is still sometimes displayed with the symbols AA, or CLA or c.l.a. Many instruments still in use employ an average deviation from the roughness centerline which is the root mean square (rms), also expressed in microinches (R_q). While still used frequently, rms actually has been obsolete since about 1950. Roughness measuring instruments calibrated in rms read approximately 25 percent higher on a given surface than those instruments calibrated for R_a (see table 18.2-1). The difference is usually much less than the point-to-point variations on any given machined surface.

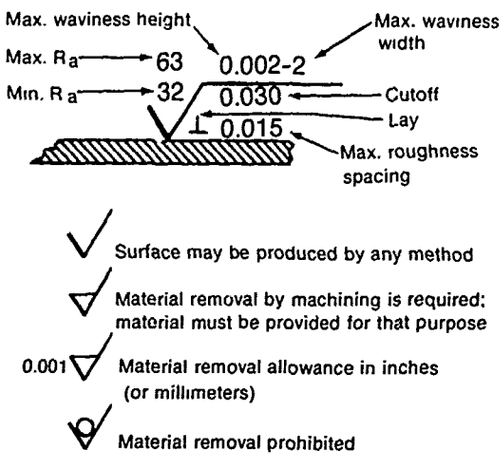


Figure 18.2-3 Surface texture symbols used for drawings or specifications. In this example, all values are in inches except R_a values, which are in microinches (millionths of an inch). Metric values (millimeters and micrometers, respectively) are used on metric drawings. (Based on ANSI Y14.36-1978)

TABLE 18.2-1 Ratio of Root Mean Square Roughness to Arithmetic Average Roughness Values

Root mean square roughness:	R_q
Arithmetic average roughness:	R_a
Theoretical ratio of sine waves, R_q/R_a:	1.11
Actual ratios of R_q/R_a for various processes:	
turning	1.17 to 1.26
milling	1.16 to 1.40
surface grinding	1.22 to 1.27
plunge grinding	1.26 to 1.28
soft honing	1.29 to 1.48
hard honing	1.50 to 2.10
electrical discharge machining	1.24 to 1.27
shot peening	1.24 to 1.28
Practical first approximation of R_q/R_a:	
for most processes	1.25
for honing	1.45

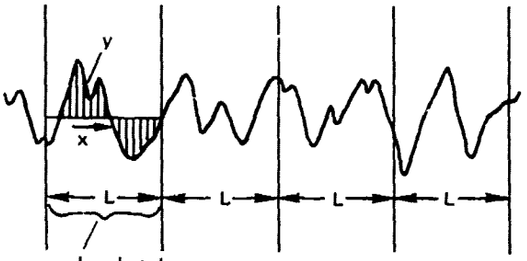
SOURCE: J. Peters; P. Vanherck; and M. Sastrodinoto, Assessment of surface typology analysis techniques, *Annals of the CIRP* 28/2, 1979.

The roughness width (or sampling) cutoff is the greatest spacing of repetitive surface irregularities to be included in the measurement of the average roughness height (figure 18.2-2). It is specified in inches and is placed below the horizontal extension of the check mark. A waviness height specification is rated in inches as the peak-to-valley distance; and waviness spacing or width, also rated in inches, is the spacing of successive peaks or valleys (figure 18.2-2). Waviness height and waviness width values are placed above the horizontal extension of the check mark. The symbol designating the lay is placed under the extension of

R_a R_q

R_a is the universally recognized parameter of roughness. It is the arithmetic mean of the departures y of the profile from the mean line. It is normally determined as the mean results of several consecutive sampling lengths L

R_q is the corresponding rms parameter.

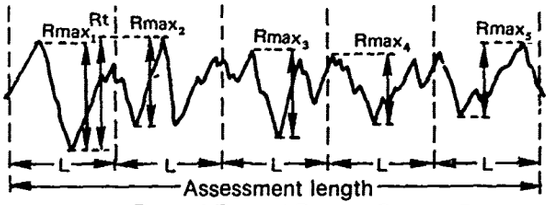


$$R_a = \frac{1}{L}\int_0^L |y|\,dx$$

$$R_q = \sqrt{\frac{1}{L}\int_0^L y^2\,(x)dx}$$

R_t R_{max} R_{tm}

R_t is the maximum peak-to-valley height within the assessment length. R_{max} is the maximum peak-to-valley height within a sampling length L. But because the value can be greatly affected by a spurious scratch or particle of dirt on the surface, it is more usual to use the average (R_{tm}) of five consecutive sampling lengths.

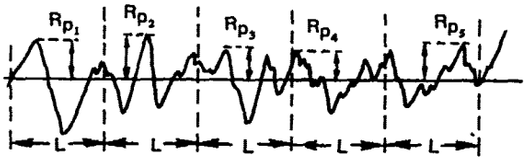


$$R_{tm} = \frac{Rmax_1 + Rmax_2 + Rmax_3 + Rmax_4 + Rmax_5}{5}$$

$$R_{tm} = 1/5 \sum_{i=1}^{i=5} Rmax_i$$

R_p R_{pm}

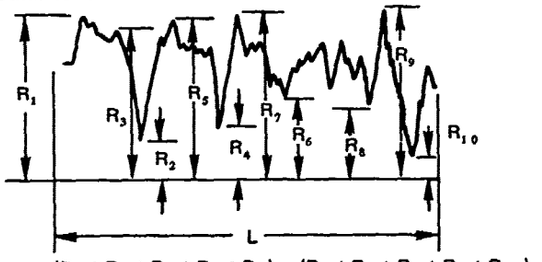
R_p is the maximum profile height from the mean line within the sampling length. R_{pm} is the mean value of R_p determined over 5 sampling lengths.



$$R_{pm} = \frac{R_{p_1} + R_{p_2} + R_{p_3} + R_{p_4} + R_{p_5}}{5} = 1/5 \sum_{i=1}^{i=5} R_{p_i}$$

R_z

Ten-Point Height is the average distance between the five highest peaks and the five deepest valleys within the sampling length and measured perpendicular to it.



$$R_z = \frac{(R_1 + R_3 + R_5 + R_7 + R_9) - (R_2 + R_4 + R_6 + R_8 + R_{10})}{5}$$

Pc

Peak count is the number of peak/valley pairs per inch projecting through a band of width b centered about the mean line.

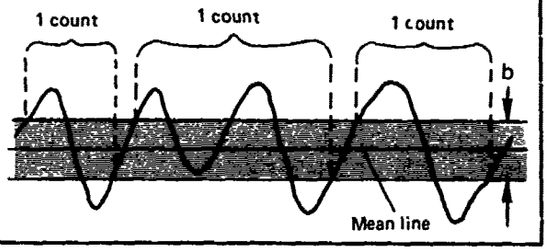


Figure 18.2-4 Some commonly used surface texture symbols and their definitions. (Based on ANSI B46.1-1978)

18.2 Surface Texture

the check mark. This symbol indicates the direction of the lay relative to the nominal surface. Figure 18.2-5 explains the various symbols used to designate lay. The pitted nondirectional or protuberant designation of lay, P, is useful to describe surfaces produced by some of the nontraditional machining operations. The surface texture symbol also can designate the extent of material removal desired—from none to any amount, as shown in figure 18.2-3.

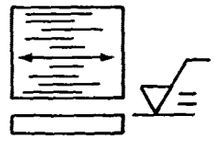
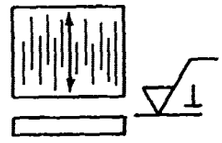
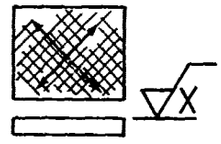
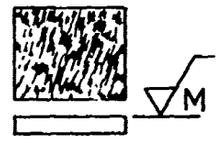
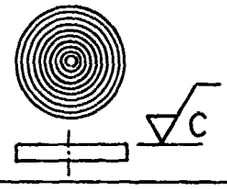
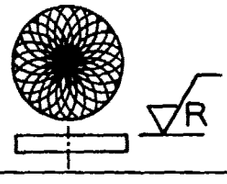
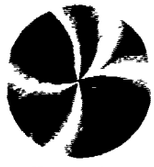
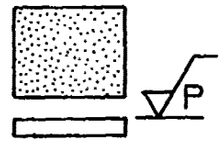
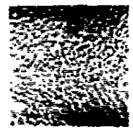
Lay Symbol	Meaning	Example Showing Direction of Tool Marks	Photographs of Examples
=	Lay approximately parallel to the line representing the surface to which the symbol is applied.		
⊥	Lay approximately perpendicular to the line representing the surface to which the symbol is applied.		
X	Lay anglular in both directions to line representing the surface to which the symbol is applied.		
M	Lay multidirectional.		
C	Lay approximately circular relative to the center of the surface to which the symbol is applied.		
R	Lay approximately radial relative to the center of the surface to which the symbol is applied.		
P	Lay particulate, non-directional, or protuberant.		

Figure 18.2-5 Lay symbols for surface texture designation. (Based on ANSI Y14.36-1978)

SURFACE TEXTURE MEASUREMENT

The most prevalent measuring technique for surface texture employs a mechanical-electronic device whose readout indicates the roughness of the surface profile taken during the passage of a small radius stylus over a short straight line path on the surface. The most common diamond stylus has a 0.0004 inch [10 μm] radius and usually is used with a 0.030 inch [0.8 mm] cutoff width. The total stylus travel is usually 20 to 60 times the cutoff width with the electronic circuitry continuously averaging the readings over the set cutoff width. These instruments can read average roughness, R_a, peak count or other roughness designations depending on the particular instrument design.

It should be kept in mind that electronic surface measuring devices generally indicate the roughness but do not indicate the physical character of the surface. Several surfaces can, in effect, be quite different in appearance and still yield similar roughness values, as shown in figure 18.2-6. One approach to more exactly describing the surface roughness is the microtopographic map, as shown in figure 18.2-7. These maps are made by successive, closely spaced stylus generated traces. A still more detailed examination is sometimes made using the scanning electron microscope (SEM). The series of views with SEM shown in figure 18.2-8 utilizes increasing magnifications of 20X, 200X, 1000X, 2000X and 5000X which are easy to relate to the view with a 10X hand-held magnifier.

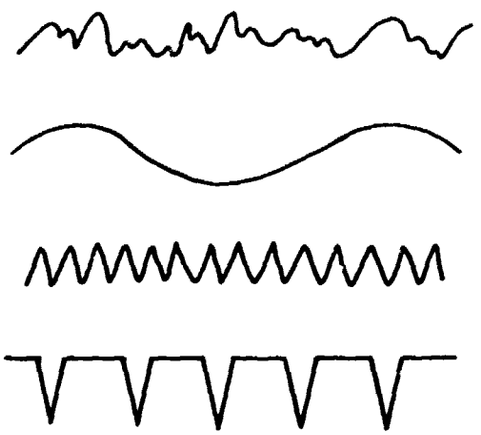


Figure 18.2-6 Sketches of cross-sections of surfaces greatly different in character but having approximately the same surface finish level.

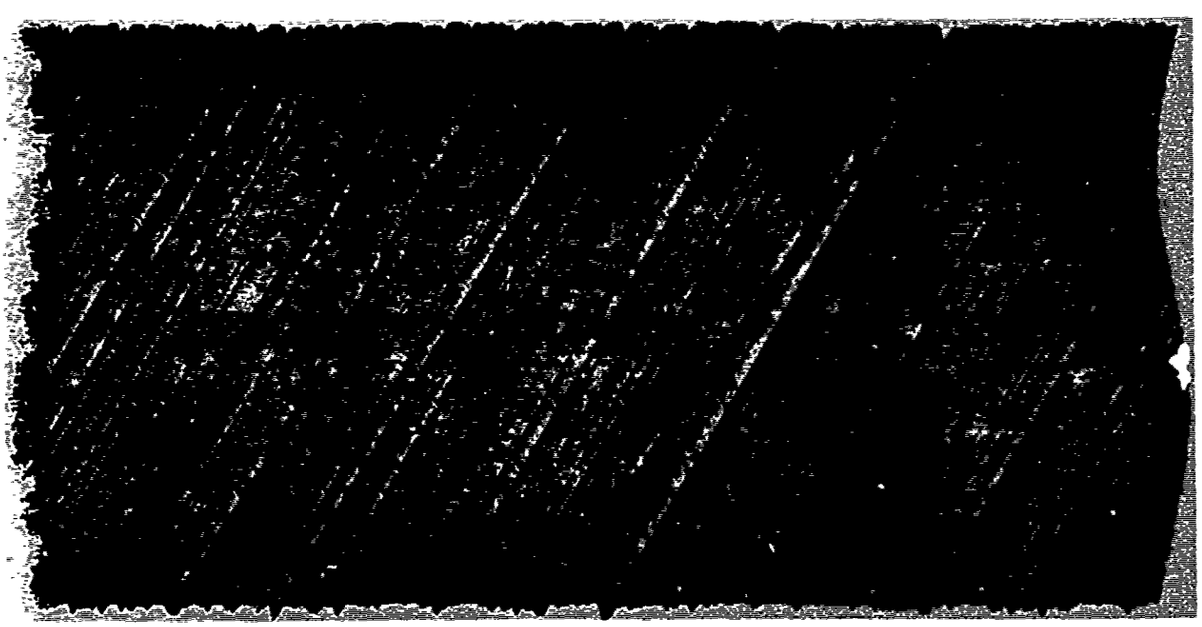


Figure 18.2-7 Microtopographic map of Blanchard-ground surface of stainless steel. 200X in X-Y plane, 2000X in Z direction (Courtesy of Gould Inc.)

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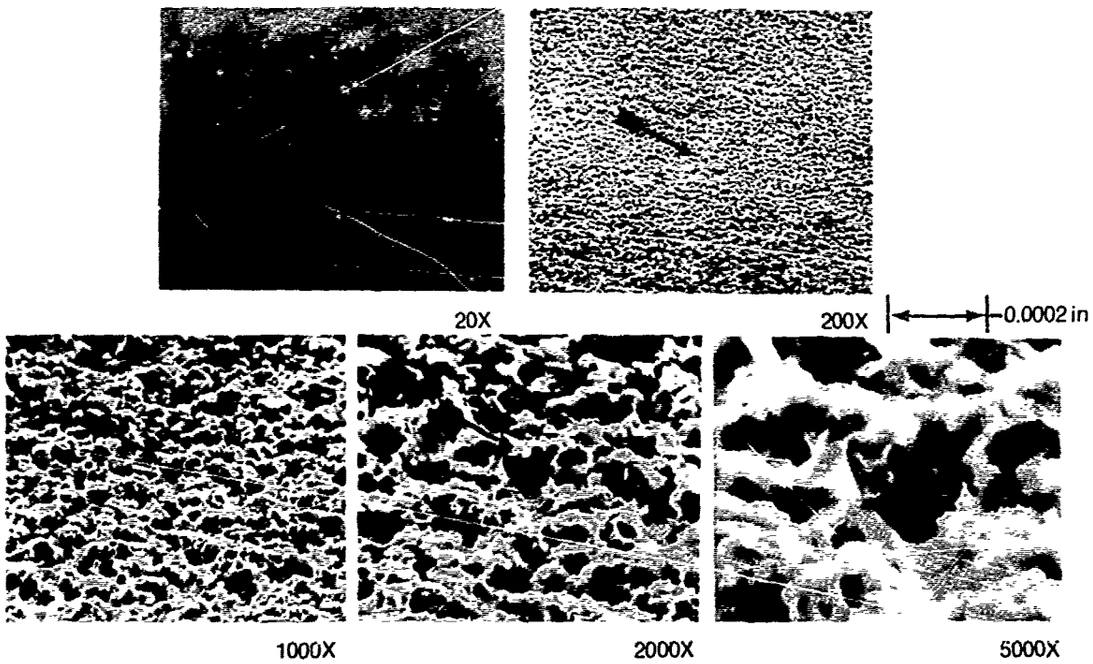


Figure 18.2–8 Scanning electron microscope (SEM) views taken at a 55° angle of a typical surface of 17-4 PH stainless steel produced by electrochemical machining (ECM). Arithmetic average roughness (R_a) was 29 microinches [0.74 μm], and maximum peak-to-valley roughness height (R_t) was 152 microinches [3.86 μm].

SURFACE TEXTURE PRODUCED BY THE MACHINING PROCESS

To a large degree the surface texture produced by a material removal process is characteristic for that particular process. The range of roughnesses typically obtained for a variety of manufacturing processes is shown in figure 18.2-9. This chart also indicates that it is possible to exceed the usual range under unusual or specially controlled conditions.

The selection of surface texture values involves more than merely designating a particular process. The ability of a processing operation to produce a specific surface roughness depends on many factors. In turning, for example, the surface roughness is geometrically related to the nose radius of the tool and the feed per revolution. For surface grinding, the final surface depends on the type of grinding wheel, the method of wheel dressing, the wheel speed, the table speed, cross feed and down feed, and the grinding fluid. For electrical discharge machining (EDM), the roughness level is related directly to the individual spark discharge energy level. A change in any of the process operating parameters may have a significant effect on the final surface produced.

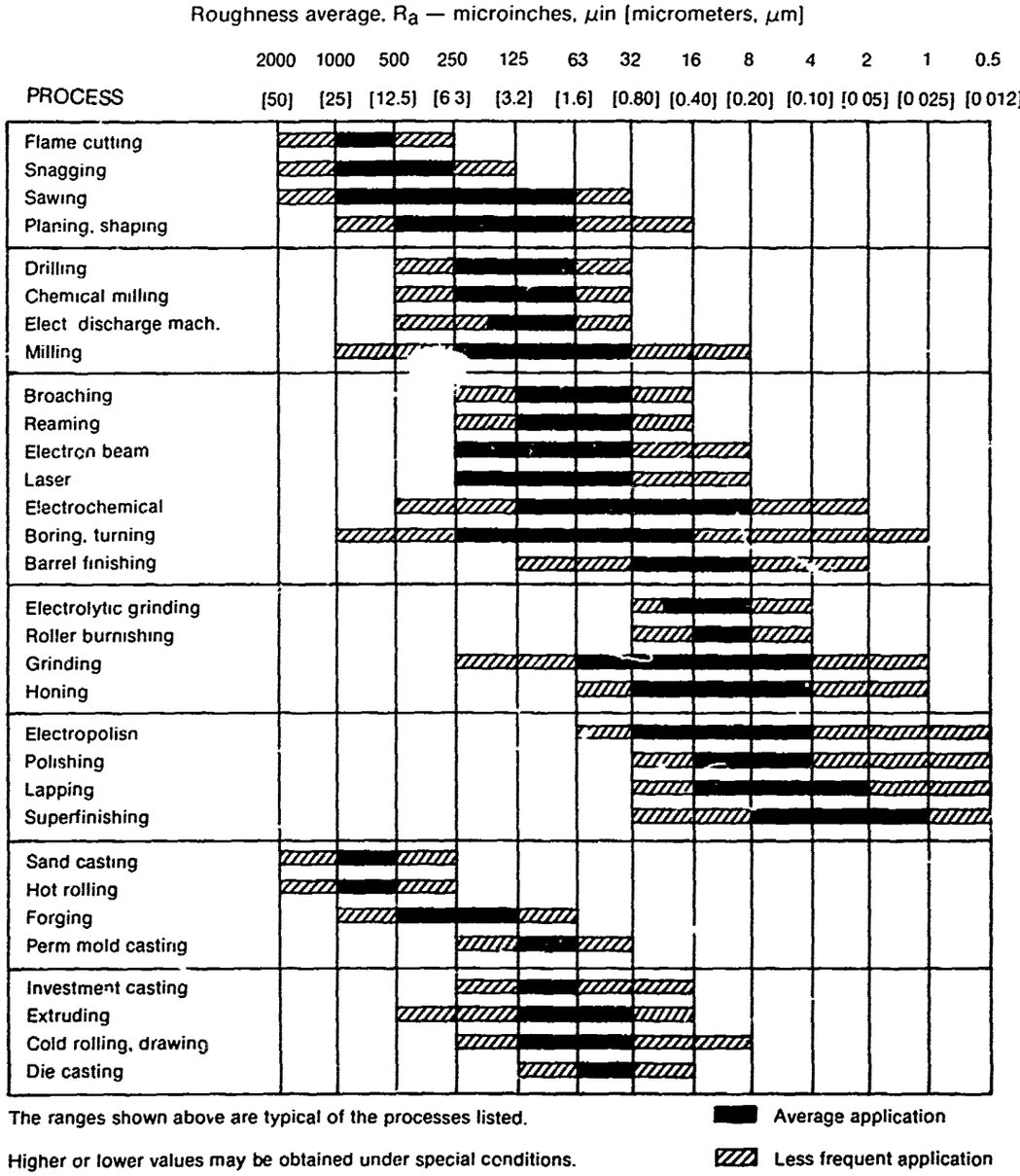


Figure 18.2-9 Surface roughness produced by common production methods. (From ANSI B46.1-1978).

18.2 Surface Texture

MACHINING COST AND SURFACE TEXTURE

The cost of producing a machined surface increases with increasing requirements for finer finishes. Certain machining operations, such as rough turning and milling, are necessary to shape a component to its required dimensions. Additional operations to refine the surface are needed only to permit the surface to perform functions which it could not otherwise perform. A surface roughness of 63 microinches [1.6 μm] or coarser can be obtained at a reasonable cost by general roughing and semi-finishing operations. The relationship of surface texture to the cost of machining is discussed further in section 21.

DIMENSIONAL TOLERANCE VERSUS SURFACE TEXTURE

There is a direct relationship between the dimensional tolerance of a part and its permissible surface roughness since the roughness measurement involves the average linear deviation of the actual surface from the nominal surface defined by the dimension. If the deviations induced by the surface roughness exceed those permitted by the dimensional tolerance, the dimension will be subject to an uncertainty beyond the tolerance, as shown in figure 18.2-10. On most surfaces the total profile height is approximately four times the measured (arithmetic average) roughness. When measurements are made on a diameter of a part, this value would be doubled. It follows that the roughness value on a diameter should not exceed one-eighth the dimensional tolerance on the diameter if useful dimensional controls are to be maintained.

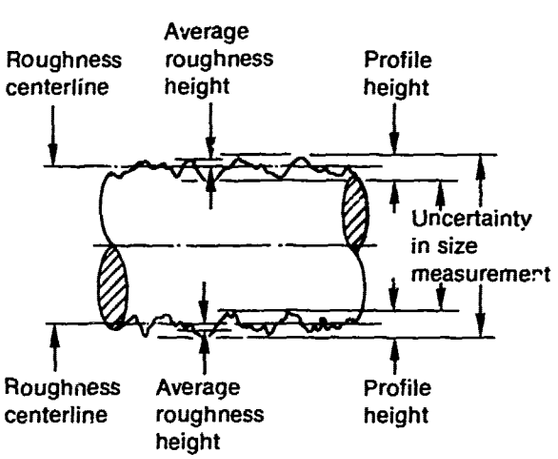


Figure 18.2-10 Uncertainty in size measurement in relation to surface roughness parameters for a cylindrical surface. (From ANSI B46.1-1978).

Each application must be evaluated on its own merit. Table 18.2-2, if used with discretion, may serve as a guide to the surface roughness values that may be necessary where machine work must be held to close tolerance for other reasons than merely surface texture. It must be further realized that the practical control of tolerance is also influenced by the size of the part, the overall size of the surface being cut, and the material removal operations involved. A chart showing how attainable dimensional tolerances tend to vary as a function of part size is shown in figure 18.2-11.

TABLE 18.2-2 Guide to Surface Roughness Values for Close Tolerance Machine Work

DIMENSIONAL TOLERANCES		SURFACE ROUGHNESS	
in	mm	μin	μm
Below 0.0002	Below 0.005	Below 8	Below 0.2
0.0002 to 0.0005	0.05 to 0.012	5 to 16	0.2 to 0.4
0.0005 to 0.0010	0.012 to 0.025	16 to 32	0.4 to 0.8
0.0010 to 0.0020	0.025 to 0.05	32 to 63	0.8 to 1.6
0.0020 to 0.0100	0.05 to 0.25	63 to 250	1.6 to 6.3

SURFACE TEXTURE AND QUALITY ASSURANCE

Quality assurance for the surfaces produced by material removal processes should include assessment of the surface roughness and all other surface texture factors. This does not imply that the effect of scratches, tool marks, sharp corners and other geometric considerations can be overlooked. It is well established that all of these elements can produce stress concentrations that can lead to premature fatigue failures. Historically, surface roughness has been the prime criterion for surface quality and a guide to acceptable fatigue strength. Some recent data indicate that for some alloys surface roughness is not the critical criterion for high cycle fatigue strength. Section 18.3 discusses this matter in greater detail.

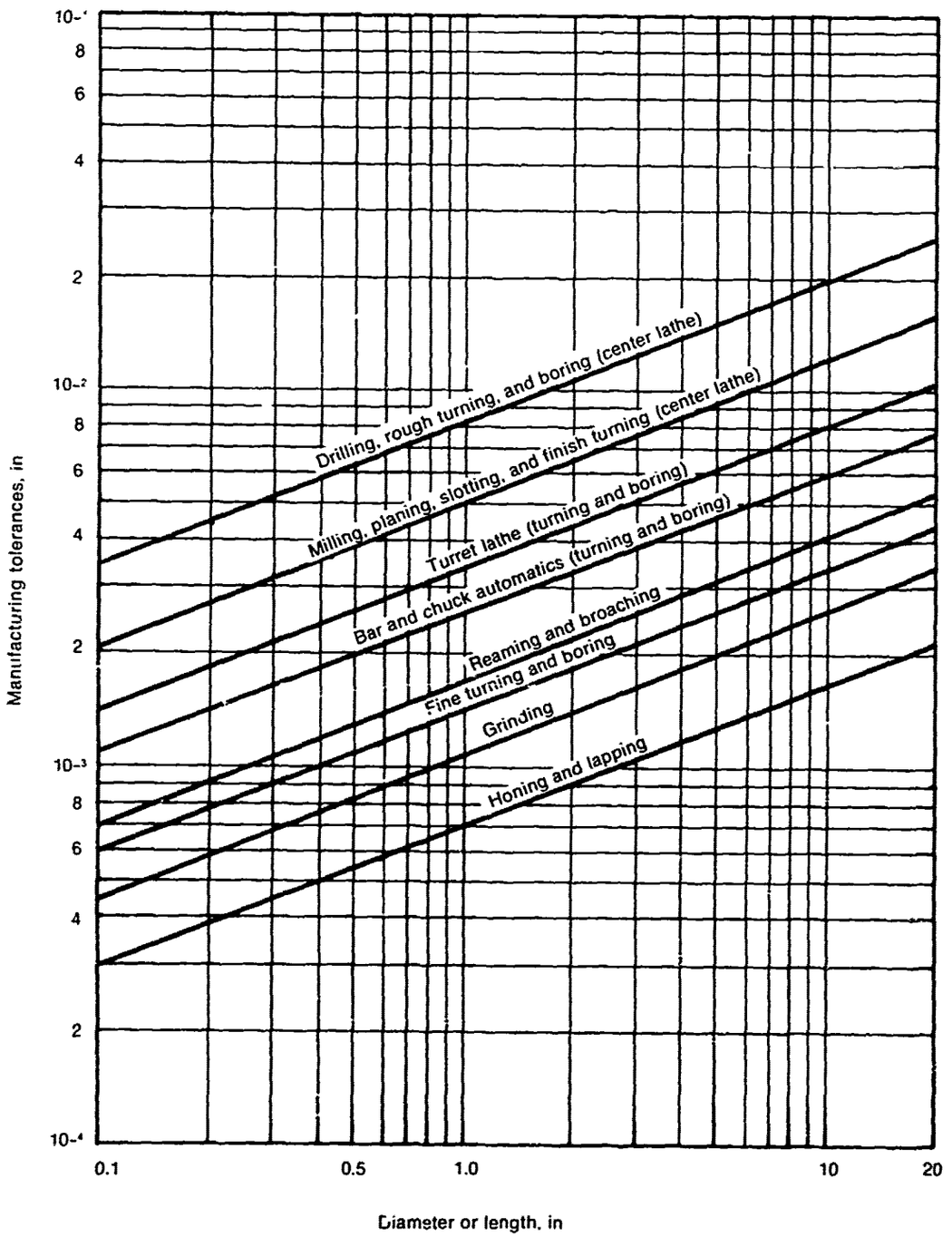


Figure 18.2–11 General effect of part size on manufacturing tolerances. (Adapted from *Manufacturing planning and estimating handbook*. New York: McGraw-Hill, 1963, p. 20–23)

18.2 Surface Texture

PREFERRED ROUGHNESS VALUES

With all the factors that can influence the generation of a surface roughness value, with the dearth of data linking a specific roughness value to the function performed by a specific surface, and with the variability introduced by the minute sample used in most measuring techniques, it is impractical to place undue emphasis on achieving a specific roughness number. To minimize the variety of drawing callouts, the American National Standards Institute in the standard, ANSI Y14.36-1978, promotes the use of preferred values for average roughess (R_a), roughness cutoff length and maximum waviness height. These values are listed in table 18.2-3.

TABLE 18.2-3 Preferred Values for Arithmetic Average Roughness (R_a), Cutoff Length, and Maximum Waviness Height

ARITHMETIC AVERAGE ROUGHNESS (R_a)		STANDARD ROUGHNESS SAMPLING LENGTH (CUTOFF)†		MAXIMUM WAVINESS HEIGHT	
μin	μm	in	mm	in	mm
0.5	0.012	0.003	0.08	0.00002	0.0005
1*	0.025*	0.010	0.25	0.00003	0.0008
2*	0.050*	0.030	0.80	0.00005	0.0012
3	0.075	0.1	2.5	0.00008	0.0020
4*	0.10*	0.3	8.0	0.0001	0.0025
5	0.125	1.0	25.0	0.0002	0.005
6	0.15			0.0003	0.008
8*	0.20*			0.0005	0.012
10	0.25			0.0008	0.020
13	0.32			0.001	0.025
16*	0.40*			0.002	0.05
20	0.50			0.003	0.08
25	0.63			0.005	0.13
32*	0.80*			0.008	0.20
40	1.00			0.010	0.25
50	1.25			0.015	0.38
63*	1.60*			0.020	0.50
80	2.0			0.030	0.80
100	2.5				
125*	3.2*				
160	4.0				
200	5.0				
250*	6.3*				
320	8.0				
400	10.0				
500*	12.5*				
600	15				
800	20				
1000*	25*				

SOURCE: ANSI Y14.36-1978.

*Recommended

†When no value is specified, the value of 0 030 inch [0.8 mm] applies.

THEORETICAL ROUGHNESS PRODUCED BY MILLING CUTTERS AND BY LATHE TOOLS

It is possible to calculate the theoretical surface roughness produced by face milling cutters in a milling operation and by lathe tools in turning. The theoretical surface roughness is important because it represents the *best* finish that can be obtained with a sharp tool. The actual surface roughness usually will be poorer than this because built-up edge is present.

For face milling, the cutter tooth can be classified according to one of the following common configurations:[2]

Type A: Zero nose radius
Type B: Round
Type C: Nose radius, end cutting edge angle and side cutting edge angle

These configurations are shown in figure 18.2-12. Formulas have been developed which determine the arithmetic average roughness, R_a, and the peak-to-valley roughness height, R_t, for these configurations.[3]

The theoretical surface roughness produced by a Type-A tooth in face milling is a function of the side cutting edge angle (SCEA), the end cutting edge angle (ECEA) and the feed per tooth. Calculated values of R_a and R_t for this tooth configuration are contained in tables 18.2-4 through 18.2-8.

The theoretical roughness produced by the round Type-B tooth in milling is a function of the tooth radius and the feed per tooth. Table 18.2-9 contains calculated values of R_a and R_t for this configuration.

The Type-C tooth produces theoretical roughness values which are a function of the nose radius, the ECEA and the feed per tooth. Values R_a and R_t that were calculated for this configuration are given in tables 18.2-10 through 18.2-19.

For turning operations, lathe tools can be characterized as either Type B or Type C (see figure 18.2-13). For common Type-C tools, the theoretical surface roughness is determined by the nose radius, the ECEA and the feed per revolution. When a round Type-B tool is used, theoretical roughness is a function of the tool radius and the feed per revolution. The similarity between the roughness determinations for the Type-B and Type-C configurations for both the turning tools and the milling cutters results in identical sets of theoretical roughness values for each tool type in each operation. Hence, the table of theoretical values of R_a and R_t values for the Type-B tooth in milling (table 18.2-9) applies equally to the Type-B tool in turning. Similarly, the values in tables 18.2-10 through 18.2-19 for the Type-C tooth in milling apply equally to the Type-C tool in turning.

A series of graphs depicts the arithmetic average surface roughness for the various tool configurations as follows:

Type A: Zero-radius face milling cutter: figure 18.2-14
Type B: Round tool; figure 18.2-15
Type C: Tool containing a nose radius plus end cutting edge angle; figures 18.2-16, 18.2-17, and 18.2-18

As previously mentioned, the actual surface roughness generally will be poorer than that calculated from geometric considerations such as shown in tables 18.2-4 through 18.2-19. (The theoretical calculations all assume that the cutting conditions are such that the tool profile is duplicated exactly in the workpiece surface.) During the process of chip formation, a built-up edge or plastically deformed material may be produced at the cutting edge. Most of this built-up edge breaks off and flows away with the chip. However, part of this built-up edge can remain welded to the finished workpiece surface and adds to the surface roughness, as shown in figure 18.2-19. The presence of a built-up edge can increase the surface roughness by a factor of 1.2 to 2.5. The added roughness, or the amount of built-up edge, is a function of the cutting tool material and the work material. The amount of built-up edge present on the surface can be minimized by using higher cutting speeds and by using chemically active cutting fluids. Additional factors which can add to the surface roughness include chatter, vibration and tool wear.

Special tool shapes can create finer or micro-finishes. A "wiper" blade, figure 18.2-20, is one such tool shape used. Its broad, convex face reduces feed marks. Normally only one wiper blade is required in multiblade milling cutters. Higher cutting speeds do not appear to reduce the efficiency of wiper blades.

[2]Type A, B and C tools are the same designations used by G. R. Dickinson in his paper, "A survey of factors affecting surface finish," *Proceedings, Institution of Mechanical Engineers* 182 (Part 3K, 1968): 135-147.

[3]H. L. Fischer and J. T. Elrod, "Surface finish as a function of tool geometry and feed—A theoretical approach," *Microtecnic* 25 (April 1971): 175-178.

18.2 Surface Texture

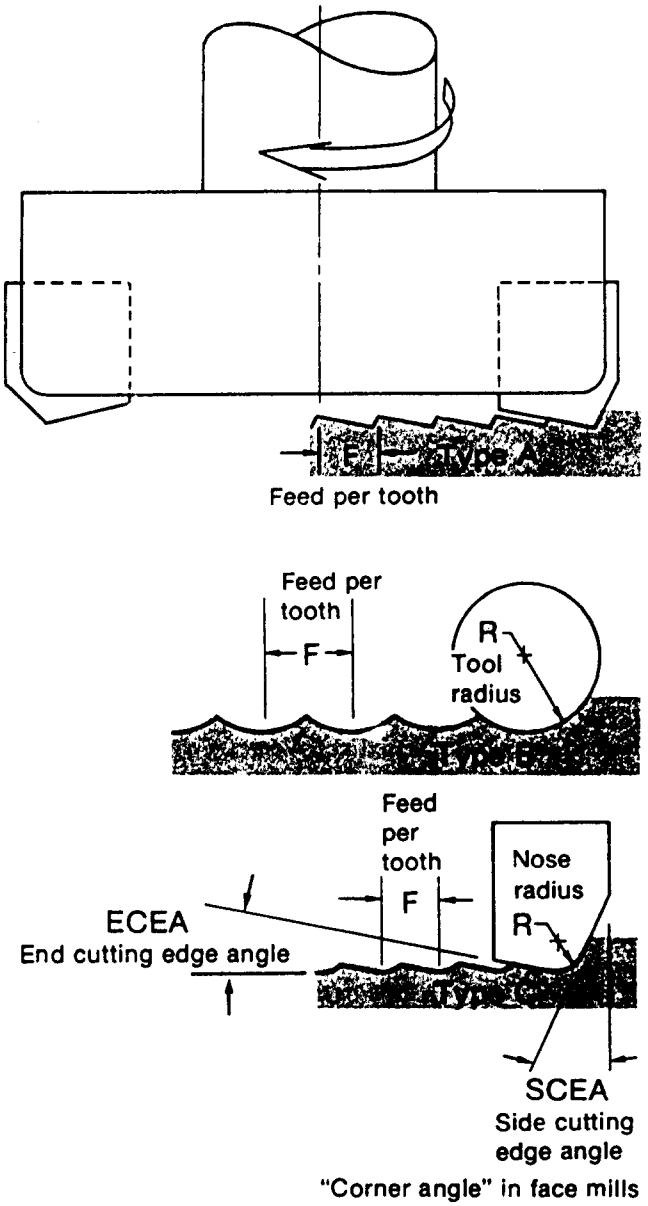


Figure 18.2–12 Surface produced by face milling with the types of tools used in the theoretical surface finish calculations.

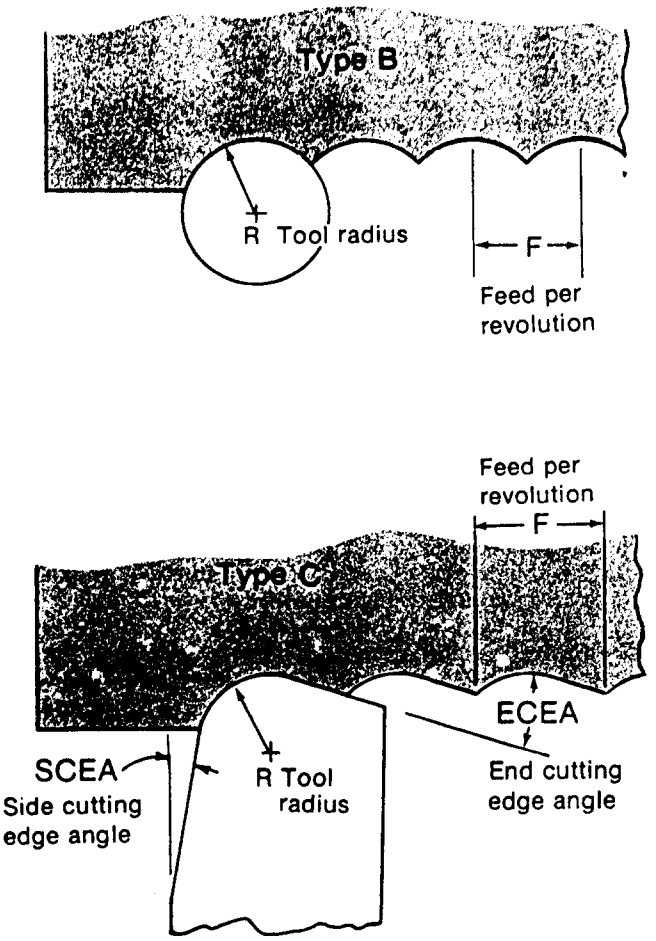


Figure 18.2–13 Surfaces produced by turning with the types of tools used in the theoretical surface finish calculations.

TABLE 18.2-4 THEORETICAL Values for Arithmetic-Average Roughness (R_a) and Maximum Peak-to-Valley Roughness Height (R_t) for Milling—Tool Type A

ZERO NOSE RADIUS																SCEA=0°
FEED PER TOOTH	1° ECEA		2° ECEA		3° ECEA		4° ECEA		5° ECEA		6° ECEA		7° ECEA		8° ECEA	
	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t
in	microinches															
0.001	4.4	17.	8.7	35.	13.	52.	17.	70.	22.	87.	26.	105.	31.	123.	35.	141.
0.002	8.7	35.	17.	70.	26.	105.	35.	140.	44.	175.	53.	210.	61.	246.	70.	281.
0.003	13.	52.	26.	105.	39.	157.	52.	210.	66.	262.	79.	315.	92.	368.	105.	422.
0.004	17.	70.	35.	140.	52.	210.	70.	280.	87.	350.	105.	420.	123.	491.	141.	562.
0.005	22.	87.	44.	175.	66.	262.	87.	350.	109.	437.	131.	526.	153.	614.	176.	703.
0.006	26.	105.	52.	210.	79.	314.	105.	420.	131.	525.	158.	631.	184.	737.	211.	843.
0.007	31.	122.	61.	244.	92.	367.	122.	489.	153.	612.	184.	736.	215.	859.	246.	984.
0.008	35.	140.	70.	279.	105.	419.	140.	559.	175.	700.	210.	841.	246.	982.	281.	1124.
0.009	39.	157.	79.	314.	118.	472.	157.	629.	197.	787.	236.	946.	276.	1105.	316.	1265.
0.010	44.	175.	87.	349.	131.	524.	175.	699.	219.	875.	263.	1051.	307.	1228.	351.	1405.
0.012	52.	209.	105.	419.	157.	629.	210.	839.	262.	1050.	315.	1261.	368.	1473.	422.	1686.
0.014	61.	244.	122.	489.	183.	734.	245.	979.	306.	1225.	368.	1471.	430.	1719.	492.	1968.
0.016	70.	279.	140.	559.	210.	839.	280.	1119.	350.	1400.	420.	1682.	491.	1965.	562.	2249.
0.018	79.	314.	157.	629.	236.	943.	315.	1259.	394.	1575.	473.	1892.	553.	2210.	632.	2530.
0.020	87.	349.	175.	698.	262.	1048.	350.	1399.	437.	1750.	526.	2102.	614.	2456.	703.	2811.
0.025	109.	436.	218.	873.	328.	1310.	437.	1748.	547.	2187.	657.	2628.	767.	3070.	878.	3514.
0.030	131.	524.	262.	1048.	393.	1572.	524.	2098.	656.	2625.	788.	3153.	921.	3684.	1054.	4216.
0.035	153.	611.	306.	1222.	459.	1834.	612.	2447.	766.	3062.	920.	3679.	1074.	4297.	1230.	4919.
0.040	175.	698.	349.	1397.	524.	2096.	699.	2797.	875.	3500.	1051.	4204.	1228.	4911.	1405.	5622.
0.045	196.	785.	393.	1571.	590.	2358.	787.	3147.	984.	3937.	1182.	4730.	1381.	5525.	1581.	6324.
0.050	218.	873.	437.	1746.	655.	2620.	874.	3496.	1094.	4374.	1314.	5255.	1535.	6139.	1757.	7027.
mm	micrometers															
0.020	0.09	0.35	0.17	0.70	0.26	1.0	0.35	1.4	0.44	1.7	0.53	2.1	0.61	2.5	0.70	2.8
0.040	0.17	0.70	0.35	1.4	0.52	2.1	0.70	2.8	0.87	3.5	1.1	4.2	1.2	4.9	1.4	5.6
0.060	0.26	1.0	0.52	2.1	0.79	3.1	1.0	4.2	1.3	5.2	1.6	6.3	1.8	7.4	2.1	8.4
0.080	0.35	1.4	0.70	2.8	1.0	4.2	1.4	5.6	1.7	7.0	2.1	8.4	2.5	9.8	2.8	11.
0.100	0.44	1.7	0.87	3.5	1.3	5.2	1.7	7.0	2.2	8.7	2.6	11.	3.1	12.	3.5	14.
0.120	0.52	2.1	1.0	4.2	1.6	6.3	2.1	8.4	2.6	10.	3.2	13.	3.7	15.	4.2	17.
0.140	0.61	2.4	1.2	4.9	1.8	7.3	2.4	9.8	3.1	12.	3.7	15.	4.3	17.	4.9	20.
0.160	0.70	2.8	1.4	5.6	2.1	8.4	2.8	11.	3.5	14.	4.2	17.	4.9	20.	5.6	22.
0.180	0.79	3.1	1.6	6.3	2.4	9.4	3.1	13.	3.9	16.	4.7	19.	5.5	22.	6.3	25.
0.200	0.87	3.5	1.7	7.0	2.6	10.	3.5	14.	4.4	17.	5.3	21.	6.1	25.	7.0	28.
0.250	1.1	4.4	2.2	8.7	3.3	13.	4.4	17.	5.5	22.	6.6	26.	7.7	31.	8.8	35.
0.300	1.3	5.2	2.6	10.	3.9	16.	5.2	21.	6.6	26.	7.9	32.	9.2	37.	11.	42.
0.350	1.5	6.1	3.1	12.	4.6	18.	6.1	24.	7.7	31.	9.2	37.	11.	43.	12.	49.
0.400	1.7	7.0	3.5	14.	5.2	21.	7.0	28.	8.7	35.	11.	42.	12.	49.	14.	56.
0.450	2.0	7.9	3.9	16.	5.9	24.	7.9	31.	9.8	39.	12.	47.	14.	55.	16.	63.
0.500	2.2	8.7	4.4	17.	6.6	26.	8.7	35.	11.	44.	13.	53.	15.	61.	18.	70.
0.600	2.6	10.	5.2	21.	7.9	31.	10.	42.	13.	52.	16.	63.	18.	74.	21.	84.
0.700	3.1	12.	6.1	24.	9.2	37.	12.	49.	15.	61.	18.	74.	21.	86.	25.	98.
0.800	3.5	14.	7.0	28.	10.	42.	14.	56.	17.	70.	21.	84.	25.	98.	28.	112.
1.000	4.4	17.	8.7	35.	13.	52.	17.	70.	22.	87.	26.	105.	31.	123.	35.	141.
1.200	5.2	21.	10.	42.	16.	63.	21.	84.	26.	105.	32.	126.	37.	147.	42.	169.

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TABLE 18.2-5 THEORETICAL Values for Arithmetic-Average Roughness (R_a) and Maximum Peak-to-Valley Roughness Height (R_t) for Milling—Tool Type A

ZERO NOSE RADIUS																SCEA=15°
FEED PER TOOTH	1° ECEA		2° ECEA		3° ECEA		4° ECEA		5° ECEA		6° ECEA		7° ECEA		8° ECEA	
	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t
in	microinches															
0.001	4.3	17.	8.6	35.	13.	52.	17.	69.	21.	85.	26.	102.	30.	119.	34.	135.
0.002	8.7	35.	17.	69.	26.	103.	34.	137.	43.	171.	51.	204.	59.	238.	68.	271.
0.003	13.	52.	26.	104.	39.	155.	51.	206.	64.	256.	77.	307.	89.	357.	102.	406.
0.004	17.	69.	35.	138.	52.	207.	69.	275.	85.	342.	102.	409.	119.	475.	135.	542.
0.005	22.	87.	43.	173.	65.	258.	86.	343.	107.	427.	128.	511.	149.	594.	169.	677.
0.006	26.	104.	52.	208.	78.	310.	103.	412.	128.	513.	153.	613.	178.	713.	203.	813.
0.007	30.	122.	61.	242.	96.	362.	120.	480.	150.	598.	179.	716.	208.	832.	237.	948.
0.008	35.	139.	69.	277.	103.	413.	137.	549.	171.	684.	204.	818.	238.	951.	271.	1084.
0.009	39.	156.	78.	311.	116.	465.	154.	616.	192.	769.	230.	920.	267.	1070.	305.	1219.
0.010	43.	174.	86.	346.	129.	517.	172.	686.	214.	855.	256.	1022.	297.	1189.	339.	1354.
0.012	52.	208.	104.	415.	155.	620.	206.	824.	256.	1026.	307.	1227.	357.	1426.	406.	1625.
0.014	61.	243.	121.	484.	181.	724.	240.	961.	299.	1197.	358.	1431.	416.	1664.	474.	1896.
0.016	69.	278.	138.	554.	207.	827.	275.	1098.	342.	1368.	409.	1636.	475.	1902.	542.	2167.
0.018	78.	313.	156.	623.	233.	930.	309.	1236.	385.	1539.	460.	1840.	535.	2140.	609.	2438.
0.020	87.	347.	173.	692.	258.	1034.	343.	1373.	427.	1710.	511.	2045.	594.	2377.	677.	2709.
0.025	109.	434.	216.	865.	323.	1292.	429.	1716.	534.	2137.	639.	2556.	743.	2972.	847.	3386.
0.030	130.	521.	259.	1038.	388.	1550.	515.	2059.	641.	2565.	767.	3067.	892.	3566.	1016.	4063.
0.035	152.	608.	303.	1211.	452.	1809.	601.	2402.	748.	2992.	894.	3578.	1040.	4161.	1185.	4740.
0.040	174.	695.	346.	1384.	517.	2067.	686.	2746.	855.	3419.	1022.	4089.	1189.	4755.	1354.	5418.
0.045	195.	782.	389.	1557.	581.	2326.	772.	3089.	962.	3847.	1150.	4600.	1337.	5349.	1524.	6095.
0.050	217.	869.	432.	1730.	646.	2584.	858.	3432.	1069.	4274.	1278.	5111.	1486.	5944.	1693.	6772.
mm	micrometers															
0.020	0.09	0.35	0.17	0.69	0.26	1.0	0.34	1.4	0.43	1.7	0.51	2.0	0.59	2.4	0.68	2.7
0.040	0.17	0.69	0.35	1.4	0.52	2.1	0.69	2.7	0.85	3.4	1.0	4.1	1.2	4.8	1.4	5.4
0.060	0.26	1.0	0.52	2.1	0.78	3.1	1.0	4.1	1.3	5.1	1.5	6.1	1.8	7.1	2.0	8.1
0.080	0.35	1.4	0.69	2.8	1.0	4.1	1.4	5.5	1.7	6.8	2.0	8.2	2.4	9.5	2.7	11.
0.100	0.43	1.7	0.86	3.5	1.3	5.2	1.7	6.9	2.1	8.5	2.6	10.	3.0	12.	3.4	14.
0.120	0.52	2.1	1.0	4.2	1.6	6.2	2.1	8.2	2.6	10.	3.1	12.	3.6	14.	4.1	16.
0.140	0.61	2.4	1.2	4.8	1.8	7.2	2.4	9.6	3.0	12.	3.6	14.	4.2	17.	4.7	19.
0.160	0.69	2.8	1.4	5.5	2.1	8.3	2.7	11.	3.4	14.	4.1	16.	4.8	19.	5.4	22.
0.180	0.78	3.1	1.6	6.2	2.3	9.3	3.1	12.	3.8	15.	4.6	18.	5.3	21.	6.1	24.
0.200	0.87	3.5	1.7	6.9	2.6	10.	3.4	14.	4.3	17.	5.1	20.	5.9	24.	6.8	27.
0.250	1.1	4.3	2.2	8.6	3.2	13.	4.3	17.	5.3	21.	6.4	26.	7.4	30.	8.5	34.
0.300	1.3	5.2	2.6	10.	3.9	16.	5.1	21.	6.4	26.	7.7	31.	8.9	36.	10.	41.
0.350	1.5	6.1	3.0	12.	4.5	18.	6.0	24.	7.5	30.	8.9	36.	10.	42.	12.	47.
0.400	1.7	6.9	3.5	14.	5.2	21.	6.9	27.	8.5	34.	10.	41.	12.	48.	14.	54.
0.450	2.0	7.8	3.9	16.	5.8	23.	7.7	31.	9.6	38.	12.	46.	13.	53.	15.	61.
0.500	2.2	8.7	4.3	17.	6.5	26.	8.6	34.	11.	43.	13.	51.	15.	59.	17.	68.
0.600	2.6	10.	5.2	21.	7.8	31.	10.	41.	13.	51.	15.	61.	18.	71.	20.	81.
0.700	3.0	12.	6.1	24.	9.0	36.	12.	48.	15.	60.	18.	72.	21.	83.	24.	95.
0.800	3.5	14.	6.9	28.	10.	41.	14.	55.	17.	68.	20.	82.	24.	95.	27.	108.
1.000	4.3	17.	8.6	35.	13.	52.	17.	69.	21.	85.	26.	102.	30.	119.	34.	135.
1.200	5.2	21.	10.	42.	16.	62.	21.	82.	26.	103.	31.	123.	36.	143.	41.	163.

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TABLE 18.2-6 THEORETICAL Values for Arithmetic-Average Roughness (R_a) and Maximum Peak-to-Valley Roughness Height (R_t) for Milling—Tool Type A

ZERO NOSE RADIUS																SCEA=30°
FEED PER TOOTH	1° ECEA		2° ECEA		3° ECEA		4° ECEA		5° ECEA		6° ECEA		7° ECEA		8° ECEA	
	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t
in	microinches															
0.001	43	17	86	34	13	51	17	67	21	83	25	99	29	115	32	130
0.002	86	35	17	68	25	102	34	134	42	167	50	198	57	229	65	260
0.003	13	52	26	103	38	153	50	202	62	250	74	297	86	344	97	390
0.004	17	69	34	137	51	203	67	269	83	333	99	396	115	459	130	520
0.005	22	86	43	171	64	254	84	336	104	416	124	495	143	573	162	650
0.006	26	104	51	205	76	305	101	403	125	500	149	595	172	688	195	780
0.007	30	121	60	240	89	356	118	470	146	583	173	694	201	803	227	910
0.008	35	138	68	274	102	407	134	538	167	666	198	793	229	917	260	1040
0.009	39	156	77	308	114	458	151	605	187	750	223	892	258	1032	292	1170
0.010	43	173	86	342	127	509	168	672	208	833	248	991	287	1147	325	1300
0.012	52	207	103	411	153	610	202	807	250	999	297	1189	344	1376	390	1560
0.014	60	242	120	479	178	712	235	941	291	1166	347	1387	401	1605	455	1820
0.016	69	276	137	548	203	814	268	1075	333	1333	395	1585	459	1835	520	2080
0.018	78	311	154	616	229	916	302	1210	375	1499	446	1784	516	2064	585	2340
0.020	86	346	171	685	254	1017	336	1344	416	1666	495	1982	573	2293	650	2600
0.025	108	433	214	856	318	1272	420	1680	521	2082	619	2477	717	2866	812	3250
0.030	130	518	257	1027	382	1526	504	2016	625	2498	743	2973	860	3440	975	3900
0.035	151	605	300	1198	445	1780	588	2352	729	2915	867	3468	1003	4013	1137	4550
0.040	173	691	342	1369	509	2035	672	2689	833	3331	991	3964	1147	4586	1300	5200
0.045	194	778	385	1540	572	2289	756	3025	937	3748	1115	4459	1290	5160	1462	5850
0.050	216	864	428	1712	636	2543	840	3361	1041	4164	1239	4955	1433	5733	1625	6500
mm	micrometers															
0.020	0.09	0.35	0.17	0.68	0.25	1.0	0.34	1.3	0.42	1.7	0.50	2.0	0.57	2.3	0.65	2.6
0.040	0.17	0.69	0.34	1.4	0.51	2.0	0.67	2.7	0.83	3.3	0.99	4.0	1.1	4.6	1.3	5.2
0.060	0.26	1.0	0.51	2.1	0.76	3.1	1.0	4.0	1.2	5.0	1.5	5.9	1.7	6.9	1.9	7.8
0.080	0.35	1.4	0.68	2.7	1.0	4.1	1.3	5.4	1.7	6.7	2.0	7.9	2.3	9.2	2.6	10.
0.100	0.43	1.7	0.86	3.4	1.3	5.1	1.7	6.7	2.1	8.3	2.5	9.9	2.9	11.	3.2	13.
0.120	0.52	2.1	1.0	4.1	1.5	6.1	2.0	8.1	2.5	10.0	3.0	12.	3.4	14.	3.9	16.
0.140	0.60	2.4	1.2	4.8	1.8	7.1	2.4	9.4	2.9	12.	3.5	14.	4.0	16.	4.5	18.
0.160	0.69	2.8	1.4	5.5	2.0	8.1	2.7	11.	3.3	13.	4.0	16.	4.6	18.	5.2	21.
0.180	0.78	3.1	1.5	6.2	2.3	9.2	3.0	12.	3.7	15.	4.5	18.	5.2	21.	5.8	23.
0.200	0.86	3.5	1.7	6.8	2.5	10.	3.4	13.	4.2	17.	5.0	20.	5.7	23.	6.5	26.
0.250	1.1	4.3	2.1	8.6	3.2	13.	4.2	17.	5.2	21.	6.2	25.	7.2	29.	8.1	32.
0.300	1.3	5.2	2.6	10.	3.8	15.	5.0	20.	6.2	25.	7.4	30.	8.6	34.	9.7	39
0.350	1.5	6.0	3.0	12.	4.5	18.	5.9	24.	7.3	29.	8.7	35.	10.	40.	11.	45.
0.400	1.7	6.9	3.4	14.	5.1	20.	6.7	27.	8.3	33.	9.9	40.	11.	46.	13.	52.
0.450	1.9	7.8	3.9	15.	5.7	23.	7.6	30.	9.4	37.	11.	45.	13.	52.	15.	58.
0.500	2.2	8.6	4.3	17.	6.4	25.	8.4	34.	10.	42.	12.	50.	14.	57.	16.	65.
0.600	2.6	10.	5.1	21.	7.6	31.	10.	40.	12.	50.	15.	59.	17.	69.	19.	78.
0.700	3.0	12.	6.0	24.	8.9	36.	12.	47.	15.	58.	17.	69.	20.	80.	23.	91.
0.800	3.5	14.	6.8	27.	10.	41.	13.	54.	17.	67.	20.	79.	23.	92.	26.	104.
1.000	4.3	17.	8.6	34.	13.	51.	17.	67.	21.	83.	25.	99.	29.	115.	32.	130.
1.200	5.2	21.	10.	41.	15.	61.	20.	81.	25.	100.	30.	119.	34.	138.	39.	156.

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18.2 Surface Texture

TABLE 18.2-7 THEORETICAL Values for Arithmetic-Average Roughness (R_a) and Maximum Peak-to-Valley Roughness Height (R_t) for Milling—Tool Type A

ZERO NOSE RADIUS																SCEA=45°
FEED PER TOOTH	1° ECEA		2° ECEA		3° ECEA		4° ECEA		5° ECEA		6° ECEA		7° ECEA		8° ECEA	
	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t
in	microinches															
0.001	4.3	17.	8.4	34	12.	50	16	65	20.	80.	24.	95.	27.	109.	31.	123.
0.002	8.6	34	17	67.	25.	100.	33.	131.	40.	161.	48.	190.	55.	219.	62.	246.
0.003	13	51	25	101	37	149.	49.	196.	60.	241.	71.	285.	82.	328.	92.	370.
0.004	17	69.	34.	135.	50	199.	65.	261.	80.	322.	95.	380.	109.	437.	123.	493.
0.005	21	86.	42.	169.	62.	249.	82.	327.	101.	402.	119.	476.	137.	547.	154.	616.
0.006	26	103.	51.	202.	75.	299.	98.	392.	121.	483.	143.	571.	164.	656.	185.	739.
0.007	30	120.	59.	236.	87	349.	114.	457.	141.	563.	166.	666.	191.	766.	216.	863.
0.008	34	137.	67.	270.	100.	398.	131.	523.	161.	644.	190.	761.	219.	875.	246.	986.
0.009	39	154	76.	304.	112.	448.	147.	588.	181.	724.	214.	856.	246.	984.	277.	1109.
0.010	43	172	84.	337.	124.	498	163.	654.	201.	805.	238.	951.	273.	1094.	308.	1232.
0.012	51	206.	101.	405.	149	598.	196.	784.	241.	965.	285.	1141.	328.	1312.	370.	1479.
0.014	60	240.	118	472.	174.	697.	229.	915.	282.	1126.	333.	1332.	383.	1531.	431.	1725.
0.016	69.	274.	135.	540.	199	797.	261.	1046.	322.	1287.	380.	1522.	437.	1750.	493.	1972.
0.018	77	309.	152	607.	224.	896.	294.	1176.	362.	1448.	428.	1712.	492.	1968.	555.	2218.
0.020	86	343.	169.	675.	249	996.	327.	1307.	402.	1609.	476.	1902.	547.	2187.	616.	2464.
0.025	107	429	211.	844.	311.	1245.	408	1634.	503.	2011.	594.	2378.	683.	2734.	770.	3081.
0.030	129	515	253.	1012	373.	1494.	490.	1961.	603.	2414.	713.	2853.	820	3281	924.	3697.
0.035	150	600	295	1181	436.	1743	572	2287.	704.	2816.	832	3329.	957.	3828.	1078.	4313.
0.040	172.	686.	337.	1350	498.	1992.	654.	2614.	805.	3218.	951.	3804.	1094.	4374.	1232.	4929.
0.045	193.	772.	380.	1518.	560.	2241.	735.	2941.	905.	3620.	1070.	4280.	1230.	4921.	1386.	5545.
0.050	214.	858.	422.	1687.	622.	2490.	817.	3268.	1006.	4023.	1189.	4755.	1367.	5468.	1540.	6161.
mm	micrometers															
0.020	0.09	0.34	0.17	0.67	0.25	1.00	0.33	1.3	0.40	1.6	0.48	1.9	0.55	2.2	0.62	2.5
0.040	0.17	0.69	0.34	1.3	0.50	2.0	0.65	2.6	0.80	3.2	0.95	3.8	1.1	4.4	1.2	4.9
0.060	0.26	1.0	0.51	2.0	0.75	3.0	0.98	3.9	1.2	4.8	1.4	5.7	1.6	6.6	1.8	7.4
0.080	0.34	1.4	0.67	2.7	1.00	4.0	1.3	5.2	1.6	6.4	1.9	7.6	2.2	8.7	2.5	9.9
0.100	0.43	1.7	0.84	3.4	1.2	5.0	1.6	6.5	2.0	8.0	2.4	9.5	2.7	11.	3.1	12.
0.120	0.51	2.1	1.0	4.0	1.5	6.0	2.0	7.8	2.4	9.7	2.9	11.	3.3	13.	3.7	15.
0.140	0.60	2.4	1.2	4.7	1.7	7.0	2.3	9.1	2.8	11.	3.3	13.	3.8	15.	4.3	17.
0.160	0.69	2.7	1.3	5.4	2.0	8.0	2.6	10.	3.2	13.	3.8	15.	4.4	17.	4.9	20.
0.180	0.77	3.1	1.5	6.1	2.2	9.0	2.9	12.	3.6	14.	4.3	17.	4.9	20.	5.5	22.
0.200	0.86	3.4	1.7	6.7	2.5	10.0	3.3	13.	4.0	16.	4.8	19.	5.5	22.	6.2	25.
0.250	1.1	4.3	2.1	8.4	3.1	12.	4.1	16.	5.0	20.	5.9	24.	6.8	27.	7.7	31.
0.300	1.3	5.1	2.5	10.	3.7	15.	4.9	20.	6.0	24.	7.1	29.	8.2	33.	9.2	37.
0.350	1.5	6.0	3.0	12.	4.4	17.	5.7	23.	7.0	28.	8.3	33.	9.6	38.	11.	43.
0.400	1.7	6.9	3.4	13.	5.0	20.	6.5	26.	8.0	32.	9.5	38.	11.	44.	12.	49.
0.450	1.9	7.7	3.8	15.	5.6	22.	7.4	29.	9.1	36.	11.	43.	12.	49.	14.	55.
0.500	2.1	8.6	4.2	17.	6.2	25.	8.2	33.	10.	40.	12.	48.	14.	55.	15.	62.
0.600	2.6	10.	5.1	20.	7.5	30.	9.8	39.	12.	48.	14.	57.	16.	66.	18.	74.
0.700	3.0	12.	5.9	24.	8.7	35.	11.	46.	14.	56.	17.	67.	19.	77.	22.	86.
0.800	3.4	14.	6.7	27.	10.0	40.	13.	52.	16.	64.	19.	76.	22.	87.	25.	99.
1.000	4.3	17.	8.4	34.	12.	50.	16.	65.	20.	80.	24.	95.	27.	109.	31.	123.
1.200	5.1	21.	10.	40.	15.	60.	20.	78.	24.	97.	29.	114.	33.	131.	37.	148.

TABLE 18.2–8 THEORETICAL Values for Arithmetic-Average Roughness (R_a) and Maximum Peak-to-Valley Roughness Height (R_t) for Milling—Tool Type A

ZERO NOSE RADIUS																SCEA=60°
FEED PER TOOTH	1° ECEA		2° ECEA		3° ECEA		4° ECEA		5° ECEA		6° ECEA		7° ECEA		8° ECEA	
	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t
in	microinches															
0.001	4.2	17.	8.2	33.	12.	48.	16.	62.	19.	76.	22.	89.	25.	101.	28.	113.
0.002	8.5	34.	16.	66.	24.	96.	31.	125.	38.	152.	44.	178.	51.	203.	57.	226.
0.003	13.	51.	25.	99.	36.	144.	47.	187.	57.	228.	67.	267.	76.	304.	85.	339.
0.004	17.	68.	33.	132.	48.	192.	62.	249.	76.	304.	89.	356.	101.	405.	113.	452.
0.005	21.	85.	41.	165.	60.	240.	78.	312.	95.	380.	111.	445.	127.	506.	141.	565.
0.006	25.	102.	49.	198.	72.	288.	94.	374.	114.	456.	133.	534.	152.	608.	170.	678.
0.007	30.	119.	58.	231.	84.	336.	109.	437.	133.	532.	156.	622.	177.	709.	198.	791.
0.008	34.	136.	66.	263.	96.	384.	125.	499.	152.	608.	178.	711.	203.	810.	226.	904.
0.009	38.	152.	74.	296.	108.	432.	140.	561.	171.	684.	200.	800.	228.	911.	254.	1017.
0.010	42.	169.	82.	329.	120.	480.	156.	624.	190.	760.	222.	889.	253.	1013.	283.	1130.
0.012	51.	203.	99.	395.	144.	577.	187.	748.	228.	912.	267.	1067.	304.	1215.	339.	1356.
0.014	59.	237.	115.	461.	168.	673.	218.	873.	266.	1064.	311.	1245.	354.	1418.	396.	1582.
0.016	68.	271.	132.	527.	192.	769.	249.	998.	304.	1216.	356.	1423.	405.	1620.	452.	1808.
0.018	76.	305.	148.	593.	216.	865.	281.	1123.	342.	1368.	400.	1601.	456.	1823.	509.	2034.
0.020	85.	339.	165.	659.	240.	961.	312.	1247.	380.	1520.	445.	1778.	506.	2025.	565.	2261.
0.025	106.	424.	206.	823.	300.	1201.	390.	1559.	475.	1899.	556.	2223.	633.	2531.	706.	2826.
0.030	127.	508.	247.	988.	360.	1441.	468.	1871.	570.	2279.	667.	2668.	759.	3038.	848.	3391.
0.035	148.	593.	288.	1153.	420.	1682.	546.	2183.	665.	2659.	778.	3112.	886.	3544.	989.	3956.
0.040	169.	678.	329.	1317.	480.	1922.	624.	2495.	760.	3039.	889.	3557.	1013.	4050.	1130.	4521.
0.045	191.	762.	370.	1482.	541.	2162.	702.	2807.	855.	3419.	1000.	4001.	1139.	4556.	1272.	5086.
0.050	212.	847.	412.	1646.	601.	2402.	780.	3119.	950.	3799.	1111.	4446.	1266.	5063.	1413.	5651.
mm	micrometers															
0.020	0.08	0.34	0.16	0.66	0.24	0.96	0.31	1.2	0.38	1.5	0.44	1.8	0.51	2.0	0.57	2.3
0.040	0.17	0.68	0.33	1.3	0.48	1.9	0.62	2.5	0.76	3.0	0.89	3.6	1.0	4.1	1.1	4.5
0.060	0.25	1.0	0.49	2.0	0.72	2.9	0.94	3.7	1.1	4.6	1.3	5.3	1.5	6.1	1.7	6.8
0.080	0.34	1.4	0.66	2.6	0.96	3.8	1.2	5.0	1.5	6.1	1.8	7.1	2.0	8.1	2.3	9.0
0.100	0.42	1.7	0.82	3.3	1.2	4.8	1.6	6.2	1.9	7.6	2.2	8.9	2.5	10.	2.8	11.
0.120	0.51	2.0	0.99	4.0	1.4	5.8	1.9	7.5	2.3	9.1	2.7	11.	3.0	12.	3.4	14.
0.140	0.59	2.4	1.2	4.6	1.7	6.7	2.2	8.7	2.7	11.	3.1	12.	3.5	14.	4.0	16.
0.160	0.68	2.7	1.3	5.3	1.9	7.7	2.5	10.0	3.0	12.	3.6	14.	4.1	16.	4.5	18.
0.180	0.76	3.0	1.5	5.9	2.2	8.6	2.8	11.	3.4	14.	4.0	16.	4.6	18.	5.1	20.
0.200	0.85	3.4	1.6	6.6	2.4	9.6	3.1	12.	3.8	15.	4.4	18.	5.1	20.	5.7	23.
0.250	1.1	4.2	2.1	8.2	3.0	12.	3.9	16.	4.7	19.	5.6	22.	6.3	25.	7.1	28.
0.300	1.3	5.1	2.5	9.9	3.6	14.	4.7	19.	5.7	23.	6.7	27.	7.6	30.	8.5	34.
0.350	1.5	5.9	2.9	12.	4.2	17.	5.5	22.	6.6	27.	7.8	31.	8.9	35.	9.9	40.
0.400	1.7	6.8	3.3	13.	4.8	19.	6.2	25.	7.6	30.	8.9	36.	10.	41.	11.	45.
0.450	1.9	7.6	3.7	15.	5.4	22.	7.0	28.	8.5	34.	10.	40.	11.	46.	13.	51.
0.500	2.1	8.5	4.1	16.	6.0	24.	7.8	31.	9.5	38.	11.	44.	13.	51.	14.	57.
0.600	2.5	10.	4.9	20.	7.2	29.	9.4	37.	11.	46.	13.	53.	15.	61.	17.	68.
0.700	3.0	12.	5.8	23.	8.4	34.	11.	44.	13.	53.	16.	62.	18.	71.	20.	79.
0.800	3.4	14.	6.6	26.	9.6	38.	12.	50.	15.	61.	18.	71.	20.	81.	23.	90.
1.000	4.2	17.	8.2	33.	12.	48.	16.	62.	19.	76.	22.	89.	25.	101.	28.	113.
1.200	5.1	20.	9.9	40.	14.	58.	19.	75.	23.	91.	27.	107.	30.	122.	34.	136.

TABLE 18.2–9 THEORETICAL Values for Arithmetic-Average Roughness (R_a) and Maximum Peak-to-Valley Roughness Height (R_t) for Turning or Milling—Tool Type B

FEED/REV. (Turning) Or FEED/TOOTH (Milling)	DIAMETER													
	0.25 in 8 mm		0.375 in 10 mm		0.50 in 12 mm		0.625 in 16 mm		0.75 in 20 mm		1.0 in 25 mm		1.25 in 32 mm		1.5 in 40 mm	
	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t
in	microinches															
0.001	0.31	1.0	0.16	0.67	0.12	0.50	0.10	0.40	0.08	0.33	0.08	0.25	0.05	0.20	0.05	0.17
0.002	1.0	4.0	0.75	2.7	0.50	2.0	0.40	1.6	0.32	1.3	0.25	1.0	0.20	0.80	0.20	0.67
0.003	2.3	9.0	1.6	6.0	1.2	4.5	0.90	3.6	0.80	3.0	0.60	2.3	0.45	1.8	0.40	1.5
0.004	4.1	16.	2.7	11.	2.1	8.0	1.7	6.4	1.5	5.3	1.0	4.0	0.80	3.2	0.70	2.7
0.005	6.4	25.	4.3	17.	3.2	13.	2.6	10.	2.2	8.3	1.7	6.3	1.5	5.0	1.1	4.2
0.006	9.2	36.	6.2	24.	4.6	18.	3.7	14.	3.2	12.	2.4	9.0	1.9	7.2	1.5	6.0
0.007	13.	49.	8.4	33.	6.3	25.	5.0	20.	4.2	16.	3.2	12.	2.6	9.8	2.5	8.2
0.008	16.	64.	11.	43.	8.2	32.	6.6	26.	5.5	21.	4.2	16.	3.5	13.	3.0	11.
0.009	21.	81.	14.	54.	10.	41.	8.3	32.	7.0	27.	5.2	20.	4.2	16.	3.7	14.
0.010	25.	100.	17.	67.	13.	50.	10.	40.	8.6	33.	6.4	25.	5.2	20.	4.4	17.
0.012	37.	144.	25.	96.	18.	72.	15.	58.	12.	48.	9.3	36.	7.4	29.	6.3	24.
0.014	50.	196.	34.	131.	25.	98.	20.	78.	17.	65.	13.	49.	10.	39.	8.5	33.
0.016	66.	256.	44.	171.	33.	128.	26.	102.	22.	85.	16.	64.	13.	51.	11.	43.
0.018	83.	324.	55.	216.	42.	162.	33.	130.	28.	108.	21.	81.	17.	65.	14.	54.
0.020	103.	401.	68.	267.	51.	200.	41.	160.	34.	133.	26.	100.	21.	80.	17.	67.
0.025	161.	627.	107.	417.	80.	313.	64.	250.	53.	208.	40.	156.	32.	125.	27.	104.
0.030	232.	903.	154.	601.	116.	450.	92.	360.	77.	300.	58.	225.	46.	180.	39.	150.
0.035	316.	1231.	210.	818.	157.	613.	126.	490.	105.	409.	79.	306.	63.	245.	52.	204.
0.040	413.	1610.	274.	1070.	206.	801.	164.	641.	137.	534.	103.	400.	82.	320.	68.	267.
0.045	523.	2042.	347.	1355.	260.	1015.	208.	811.	173.	676.	130.	507.	104.	405.	87.	338.
0.050	647.	2526.	429.	1674.	321.	1253.	257.	1002.	214.	834.	160.	625.	128.	500.	107.	417.
0.060	935.	3653.	619.	2416.	463.	1807.	370.	1443.	308.	1202.	231.	901.	185.	720.	154.	600.
0.070	1278.	5000.	844.	3296.	631.	2462.	504.	1966.	420.	1637.	315.	1227.	252.	981.	210.	817.
0.080	1677.	6573.	1105.	4316.	825.	3221.	659.	2571.	549.	2139.	411.	1603.	329.	1281.	274.	1067.
0.090	2135.	8381.	1402.	5480.	1046.	4083.	835.	3257.	695.	2710.	520.	2029.	416.	1622.	347.	1351.
0.100	2654.	10436.	1736.	6790.	1293.	5051.	1032.	4026.	858.	3348.	643.	2506.	514.	2003.	428.	1669.
mm	micrometers															
0.020	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
0.040	0.01	0.05	0.01	0.04	0.01	0.03	0.01	0.03	0.00	0.02	0.00	0.02	0.00	0.01	0.00	0.01
0.060	0.03	0.11	0.02	0.09	0.02	0.06	0.01	0.06	0.01	0.05	0.00	0.04	0.01	0.03	0.00	0.02
0.080	0.05	0.20	0.04	0.16	0.03	0.13	0.02	0.10	0.02	0.08	0.02	0.06	0.01	0.05	0.00	0.04
0.100	0.08	0.31	0.06	0.25	0.05	0.21	0.04	0.16	0.03	0.13	0.03	0.10	0.02	0.08	0.02	0.06
0.120	0.12	0.45	0.09	0.36	0.07	0.30	0.06	0.23	0.05	0.18	0.04	0.14	0.03	0.11	0.02	0.09
0.140	0.16	0.61	0.13	0.49	0.10	0.41	0.08	0.31	0.06	0.25	0.05	0.20	0.04	0.15	0.03	0.12
0.160	0.21	0.80	0.16	0.64	0.14	0.53	0.10	0.40	0.08	0.32	0.07	0.26	0.05	0.20	0.05	0.16
0.180	0.26	1.0	0.21	0.81	0.17	0.66	0.13	0.51	0.10	0.41	0.08	0.32	0.06	0.25	0.05	0.20
0.200	0.32	1.3	0.26	1.0	0.21	0.80	0.16	0.63	0.13	0.50	0.10	0.40	0.08	0.31	0.06	0.25
0.250	0.50	2.0	0.40	1.6	0.32	1.3	0.25	0.98	0.20	0.78	0.16	0.62	0.13	0.49	0.10	0.39
0.300	0.72	2.8	0.58	2.3	0.46	1.8	0.36	1.4	0.29	1.1	0.23	0.89	0.18	0.70	0.14	0.56
0.350	0.98	3.8	0.79	3.1	0.63	2.5	0.49	1.9	0.39	1.5	0.31	1.2	0.25	0.96	0.20	0.77
0.400	1.3	5.0	1.0	4.0	0.82	3.3	0.64	2.5	0.51	2.0	0.41	1.6	0.32	1.3	0.26	1.0
0.450	1.6	6.3	1.3	5.1	1.0	4.2	0.81	3.2	0.65	2.5	0.52	2.0	0.41	1.6	0.32	1.3
0.500	2.0	7.8	1.6	6.3	1.3	5.2	1.0	3.9	0.80	3.1	0.64	2.5	0.50	2.0	0.40	1.6
0.600	2.9	11.	2.3	9.0	1.8	7.5	1.4	5.6	1.2	4.5	0.92	3.6	0.72	2.8	0.58	2.3
0.700	3.9	15.	3.1	12.	2.5	10.	2.0	7.7	1.6	6.1	1.3	4.9	0.98	3.8	0.79	3.1
0.800	5.1	20.	4.1	16.	3.2	13.	2.6	10.	2.1	8.0	1.6	6.4	1.3	5.0	1.0	4.0
1.000	8.0	31.	6.4	25.	5.1	20.	4.0	16.	3.2	13.	2.6	10.	2.0	7.9	1.6	6.3
1.200	12.	45.	9.3	36.	7.4	29.	5.8	23.	4.6	18.	3.7	14.	2.9	11.	2.3	9.0
1.500	18.	71.	14.	57.	12.	45.	9.0	36.	7.2	28.	5.8	23.	4.5	18.	3.6	14.
2.000	32.	127.	26.	101.	20.	80.	16.	64.	13.	50.	10.	40.	8.0	31.	6.4	25.
2.500	51.	200.	41.	159.	32.	127.	25.	100.	20.	78.	16.	62.	13.	49.	10.	39.

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TABLE 18.2–10 THEORETICAL Values for Arithmetic-Average Roughness (R_a) and Maximum Peak-to-Valley Roughness Height (R_t) for Turning or Milling—Tool Type C

TOOL NOSE RADIUS = 0.016 in [0.20 mm]																
FEED/REV [Turning] Or FEED/TOOTH [Milling]	3° ECEA		5° ECEA		6° ECEA		10° ECEA		15° ECEA		30° ECEA		40° ECEA		45° ECEA	
	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t
in	microinches															
0.001	2.1	8.0	2.1	8.0	2.1	8.0	2.1	8.0	2.1	8.0	2.1	8.0	2.1	8.0	2.1	8.0
0.002	8.2	31	8.2	32	8.2	32	8.2	32	8.2	32	8.2	32	8.2	32	8.2	32
0.003	17	63	19	72	19	72	19	72	19	72	19	72	19	72	19	72
0.004	27	97	32	121	33	126	33	129	33	129	33	129	33	129	33	129
0.005	37	134	47	174	50	187	52	202	52	202	52	202	52	202	52	202
0.006	47	172	63	234	68	251	75	290	75	291	75	291	75	291	75	291
0.007	57	211	79	294	87	320	101	386	102	398	102	398	102	398	102	398
0.008	68	252	96	352	107	390	129	488	133	522	133	522	133	522	133	522
0.009	79	293	113	415	127	463	159	594	169	659	169	663	169	663	169	663
0.010	90	334	131	480	147	538	191	705	209	804	210	823	210	823	210	823
0.012	112	419	166	612	189	692	255	937	295	1114	305	1200	305	1200	305	1200
0.014	135	505	202	748	231	851	322	1179	388	1444	421	1659	421	1659	421	1659
0.016	158	594	239	887	275	1014	390	1430	485	1792	557	2206	557	2207	557	2207
0.018	181	683	276	1028	319	1180	460	1689	585	2154	716	2817	718	2858	718	2858
0.020	204	773	314	1171	363	1349	531	1953	688	2528	891	3470	904	3627	904	3627
0.025	264	1001	409	1537	477	1781	714	2637	955	3508	1389	5271	1492	5937	1509	6137
0.030	324	1232	507	1911	592	2224	903	3347	1233	4540	1945	7286	2224	8678	2314	9277
mm	micrometers															
0.020	0.06	0.25	0.06	0.25	0.06	0.25	0.06	0.25	0.06	0.25	0.06	0.25	0.06	0.25	0.06	0.25
0.040	0.23	0.85	0.26	0.99	0.26	1.0	0.26	1.0	0.26	1.0	0.26	1.0	0.26	1.0	0.26	1.0
0.060	0.43	1.6	0.54	2.0	0.57	2.1	0.58	2.3	0.58	2.3	0.58	2.3	0.58	2.3	0.58	2.3
0.080	0.63	2.3	0.86	3.1	0.93	3.4	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0
0.100	0.85	3.1	1.2	4.4	1.3	4.8	1.6	6.0	1.6	6.4	1.6	6.4	1.6	6.4	1.6	6.4
0.120	1.1	3.9	1.5	5.8	1.7	6.3	2.2	8.1	2.3	9.1	2.4	9.2	2.4	9.2	2.4	9.2
0.140	1.3	4.8	1.9	6.9	2.1	7.8	2.8	10.	3.2	12.	3.2	13.	3.2	13.	3.2	13.
0.160	1.5	5.6	2.2	8.3	2.5	9.4	3.5	13.	4.1	15.	4.2	17.	4.2	17.	4.2	17.
0.180	1.7	6.5	2.6	9.8	3.0	11.	4.1	15.	5.0	19.	5.4	21.	5.4	21.	5.4	21.
0.200	2.0	7.4	3.0	11.	3.4	13.	4.8	18.	6.0	22.	6.8	27.	6.8	27.	6.8	27.
0.250	2.5	9.6	3.9	15.	4.5	17.	6.8	24.	8.5	31.	11.	42.	11.	44.	11.	44.
0.300	3.1	12.	4.9	18.	5.8	21.	8.4	31.	11.	41.	16.	60.	16.	66.	17.	67.
0.350	3.7	14.	5.8	22.	6.8	25.	10.	38.	14.	51.	21.	79.	23.	92.	24.	96.

TABLE 18.2–11 THEORETICAL Values for Arithmetic-Average Roughness (R_a) and Maximum Peak-to-Valley Roughness Height (R_t) for Turning or Milling—Tool Type C

TOOL NOSE RADIUS = 0.031 in [0.40 mm]																
FEED/REV. (Turning) Or FEED/TOOTH (Milling)	3° ECEA		5° ECEA		6° ECEA		10° ECEA		15° ECEA		30° ECEA		40° ECEA		45° ECEA	
	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t
in	microinches															
0.001	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0
0.002	4.1	16.	4.1	16.	4.1	16.	4.1	16.	4.1	16.	4.1	16.	4.1	16.	4.1	16.
0.003	9.3	36.	9.3	36.	9.3	36.	9.3	36.	9.3	36.	9.3	36.	9.3	36.	9.3	36.
0.004	16.	63.	16.	64.	16.	64.	16.	64.	16.	64.	16.	64.	16.	64.	16.	64.
0.005	25.	93.	26.	100.	26.	100.	26.	100.	26.	100.	26.	100.	26.	100.	26.	100.
0.006	34.	125.	37.	144.	37.	145.	37.	145.	37.	145.	37.	145.	37.	145.	37.	145.
0.007	43.	159.	50.	191.	50.	196.	51.	197.	51.	197.	51.	197.	51.	197.	51.	197.
0.008	53.	194.	64.	242.	66.	253.	66.	257.	66.	257.	66.	257.	66.	257.	66.	257.
0.009	63.	230.	79.	294.	82.	312.	84.	326.	84.	326.	84.	326.	84.	326.	84.	326.
0.010	73.	268.	94.	349.	100.	373.	103.	403.	103.	403.	103.	403.	103.	403.	103.	403.
0.012	94.	344.	126.	462.	136.	503.	149.	579.	149.	582.	149.	582.	149.	582.	149.	582.
0.014	115.	423.	159.	581.	174.	639.	202.	771.	204.	795.	204.	795.	204.	795.	204.	795.
0.016	136.	503.	192.	704.	213.	781.	259.	975.	267.	1043.	267.	1043.	267.	1043.	267.	1043.
0.018	158.	585.	226.	830.	253.	927.	319.	1189.	339.	1318.	339.	1326.	339.	1326.	339.	1326.
0.020	180.	669.	261.	959.	294.	1076.	381.	1410.	417.	1609.	420.	1646.	420.	1646.	420.	1646.
0.025	236.	881.	350.	1291.	398.	1463.	543.	1992.	636.	2389.	665.	2613.	665.	2613.	665.	2613.
0.030	293.	1099.	441.	1634.	506.	1865.	711.	2607.	873.	3232.	972.	3842.	972.	3842.	972.	3842.
0.035	351.	1321.	534.	1985.	615.	2277.	885.	3247.	1120.	4124.	1348.	5320.	1350.	5370.	1350.	5370.
0.040	409.	1545.	628.	2343.	726.	2698.	1063.	3906.	1377.	5055.	1783.	6940.	1808.	7253.	1808.	7253.
0.045	468.	1772.	723.	2706.	839.	3127.	1244.	4583.	1640.	6020.	2263.	8684.	2355.	9456.	2360.	9581.
0.050	527.	2001.	819.	3074.	953.	3562.	1429.	5274.	1910.	7015.	2778.	10542.	2983.	11874.	3018.	12273.
0.060	646.	2465.	1013.	3821.	1185.	4447.	1805.	6693.	2466.	9080.	3889.	14572.	4447.	17356.	4629.	18554.
mm	micrometers															
0.020	0.03	0.13	0.03	0.13	0.03	0.13	0.03	0.13	0.03	0.13	0.03	0.13	0.03	0.13	0.03	0.13
0.040	0.13	0.50	0.13	0.50	0.13	0.50	0.13	0.50	0.13	0.50	0.13	0.50	0.13	0.50	0.13	0.50
0.060	0.28	1.1	0.29	1.1	0.29	1.1	0.29	1.1	0.29	1.1	0.29	1.1	0.29	1.1	0.29	1.1
0.080	0.46	1.7	0.51	2.0	0.51	2.0	0.51	2.0	0.51	2.0	0.51	2.0	0.51	2.0	0.51	2.0
0.100	0.65	2.4	0.79	3.0	0.80	3.1	0.80	3.1	0.80	3.1	0.80	3.1	0.80	3.1	0.80	3.1
0.120	0.85	3.1	1.1	4.0	1.1	4.3	1.2	4.5	1.2	4.5	1.2	4.5	1.2	4.5	1.2	4.5
0.140	1.1	3.9	1.4	5.1	1.5	5.5	1.6	6.2	1.6	6.2	1.6	6.2	1.6	6.2	1.6	6.2
0.160	1.3	4.6	1.7	6.3	1.9	6.9	2.1	8.0	2.1	8.1	2.1	8.1	2.1	8.1	2.1	8.1
0.180	1.5	5.4	2.0	7.5	2.2	8.2	2.6	9.9	2.6	10.	2.6	10.	2.6	10.	2.6	10.
0.200	1.7	6.2	2.4	8.7	2.6	9.6	3.2	12.	3.2	13.	3.2	13.	3.2	13.	3.2	13.
0.250	2.2	8.3	3.2	12.	3.6	13.	4.7	17.	5.1	20.	5.1	20.	5.1	20.	5.1	20.
0.300	2.8	10.	4.1	15.	4.7	17.	6.3	23.	7.2	27.	7.4	29.	7.4	29.	7.4	29.
0.350	3.4	13.	5.0	19.	5.7	21.	7.9	29.	9.5	36.	10.	40.	10.	40.	10.	40.
0.400	3.9	15.	5.9	22.	6.8	25.	9.6	35.	12.	44.	14.	54.	14.	54.	14.	54.
0.450	4.5	17.	6.9	26.	7.9	29.	11.	42.	14.	53.	17.	69.	17.	69.	17.	69.
0.500	5.1	19.	7.8	29.	9.0	34.	13.	48.	17.	62.	22.	85.	22.	88.	22.	88.
0.600	6.3	24.	9.7	36.	11.	42.	17.	62.	22.	82.	31.	120.	33.	132.	33.	135.
0.700	7.5	28.	12.	44.	14.	51.	21.	76.	28.	102.	42.	156.	46.	183.	48.	192.

TABLE 18.2–12 THEORETICAL Values for Arithmetic-Average Roughness (R_a) and Maximum Peak-to-Valley Roughness Height (R_t) for Turning or Milling—Tool Type C

TOOL NOSE RADIUS = 0.047 in [0.60 mm]

Feed per rev (turning) or per tooth (milling)	3° EDEA		5° EDEA		8° EDEA		10° EDEA		15° EDEA		30° EDEA		40° EDEA		45° EDEA	
	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t
in	microinches															
0.001	0.69	2.7	0.69	2.7	0.69	2.7	0.69	2.7	0.69	2.7	0.69	2.7	0.69	2.7	0.69	2.7
0.002	2.7	11	2.7	11	2.7	11	2.7	11	2.7	11	2.7	11	2.7	11	2.7	11
0.003	6.2	24	6.2	24	6.2	24	6.2	24	6.2	24	6.2	24	6.2	24	6.2	24
0.004	11	43	11	43	11	43	11	43	11	43	11	43	11	43	11	43
0.005	17	67	17	67	17	67	17	67	17	67	17	67	17	67	17	67
0.006	25	94	25	96	25	96	25	96	25	96	25	96	25	96	25	96
0.007	33	124	34	131	34	131	34	131	34	131	34	131	34	131	34	131
0.008	42	155	44	171	44	171	44	171	44	171	44	171	44	171	44	171
0.009	51	188	56	216	56	217	56	217	56	217	56	217	56	217	56	217
0.010	60	222	68	263	69	268	69	268	69	268	69	268	69	268	69	268
0.012	80	291	96	362	99	379	99	386	99	386	99	386	99	386	99	386
0.014	99	364	126	468	132	498	135	526	135	526	135	526	135	526	135	526
0.016	120	439	157	579	167	624	176	689	176	689	176	689	176	689	176	689
0.018	141	516	189	694	204	754	224	869	224	874	224	874	224	874	224	874
0.020	162	594	222	812	242	890	275	1059	277	1081	277	1081	277	1081	277	1081
0.025	215	796	305	1119	339	1243	418	1568	435	1699	435	1700	435	1700	435	1700
0.030	270	1003	392	1439	441	1614	572	2115	626	2413	630	2469	630	2469	630	2469
0.035	326	1215	480	1768	545	1999	732	2691	840	3182	864	3395	864	3395	864	3395
0.040	382	1430	570	2106	651	2393	898	3291	1070	3996	1140	4489	1140	4489	1140	4489
0.045	439	1649	662	2451	758	2797	1067	3911	1309	4848	1459	5764	1459	5764	1459	5764
0.050	497	1870	754	2801	867	3208	1240	4546	1555	5733	1824	7214	1824	7237	1824	7237
0.060	613	2318	942	3514	1090	4047	1594	5860	2065	7583	2674	10410	2712	10880	2712	10880
0.070	731	2773	1132	4242	1316	4907	1958	7218	2594	9523	3647	13937	3834	15357	3852	15670
0.080	850	3233	1325	4982	1545	5782	2330	8613	3140	11540	4707	17759	5163	20406	5270	21344
0.090	969	3697	1520	5732	1777	6671	2708	10040	3699	13621	5834	21858	6671	26034	6943	27831
mm	micrometers															
0.020	0.02	0.08	0.02	0.08	0.02	0.08	0.02	0.08	0.02	0.08	0.02	0.08	0.02	0.08	0.02	0.08
0.040	0.09	0.33	0.09	0.33	0.09	0.33	0.09	0.33	0.09	0.33	0.09	0.33	0.09	0.33	0.09	0.33
0.060	0.19	0.75	0.19	0.75	0.19	0.75	0.19	0.75	0.19	0.75	0.19	0.75	0.19	0.75	0.19	0.75
0.080	0.34	1.3	0.34	1.3	0.34	1.3	0.34	1.3	0.34	1.3	0.34	1.3	0.34	1.3	0.34	1.3
0.100	0.51	1.9	0.54	2.1	0.54	2.1	0.54	2.1	0.54	2.1	0.54	2.1	0.54	2.1	0.54	2.1
0.120	0.69	2.6	0.77	3.0	0.77	3.0	0.77	3.0	0.77	3.0	0.77	3.0	0.77	3.0	0.77	3.0
0.140	0.89	3.2	1.0	3.9	1.0	4.1	1.1	4.1	1.1	4.1	1.1	4.1	1.1	4.1	1.1	4.1
0.160	1.1	4.0	1.3	5.0	1.4	5.2	1.4	5.4	1.4	5.4	1.4	5.4	1.4	5.4	1.4	5.4
0.180	1.3	4.7	1.6	6.0	1.7	6.4	1.7	6.8	1.7	6.8	1.7	6.8	1.7	6.8	1.7	6.8
0.200	1.5	5.4	1.9	7.1	2.1	7.7	2.2	8.4	2.2	8.4	2.2	8.4	2.2	8.4	2.2	8.4
0.250	2.0	7.4	2.7	10.	3.0	11.	3.4	13.	3.4	13.	3.4	13.	3.4	13.	3.4	13.
0.300	2.5	9.4	3.6	13.	3.9	14.	4.7	18.	4.9	19.	4.9	19.	4.9	19.	4.9	19.
0.350	3.1	11.	4.4	16.	4.9	18.	6.3	23.	6.7	26.	6.7	26.	6.7	26.	6.7	26.
0.400	3.6	14.	5.3	19.	6.0	22.	7.8	28.	8.7	33.	8.8	34.	8.8	34.	8.8	34.
0.450	4.2	16.	6.2	23.	7.0	26.	9.4	35.	11.	41.	11.	44.	11.	44.	11.	44.
0.500	4.8	18.	7.1	26.	8.1	30.	11.	41.	13.	49.	14.	55.	14.	55.	14.	55.
0.600	5.9	22.	8.8	33.	10.	38.	14.	53.	18.	68.	20.	80.	20.	80.	20.	80.
0.700	7.1	27.	11.	40.	12.	46.	18.	68.	23.	84.	28.	111.	28.	113.	28.	113.
0.800	8.2	31.	13.	47.	15.	55.	22.	79.	28.	103.	37.	144.	38.	153.	38.	153.
1.000	11.	42.	18.	62.	19.	72.	29.	107.	39.	143.	58.	218.	63.	248.	64.	258.

TABLE 18.2–13 THEORETICAL Values for Arithmetic-Average Roughness (R_a) and Maximum Peak-to-Valley Roughness Height (R_t) for Turning or Milling—Tool Type C

TOOL NOSE RADIUS = 0.063 in [0.80 mm]																
FEED/REV (Turning) Or FEED/TOOTH (Milling)	3° ECEA		5° ECEA		6° ECEA		10° ECEA		15° ECEA		30° ECEA		40° ECEA		45° ECEA	
	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t
in	microinches															
0.001	0.51	2.0	0.51	2.0	0.51	2.0	0.51	2.0	0.51	2.0	0.51	2.0	0.51	2.0	0.51	2.0
0.002	2.1	8.0	2.1	8.0	2.1	8.0	2.1	8.0	2.1	8.0	2.1	8.0	2.1	8.0	2.1	8.0
0.003	4.6	18	4.6	18	4.6	18	4.6	18	4.6	18	4.6	18	4.6	18	4.6	18
0.004	8.2	32	8.2	32	8.2	32	8.2	32	8.2	32	8.2	32	8.2	32	8.2	32
0.005	13	50	13	50	13	50	13	50	13	50	13	50	13	50	13	50
0.006	18	72	18	72	18	72	18	72	18	72	18	72	18	72	18	72
0.007	25	98	25	98	25	98	25	96	25	98	25	98	25	98	25	98
0.008	33	128	33	128	33	128	33	128	33	128	33	128	33	128	33	128
0.009	41	155	42	162	42	162	42	162	42	162	42	162	42	162	42	162
0.010	50	186	51	200	51	200	51	200	51	200	51	200	51	200	51	200
0.012	68	258	74	287	74	289	74	289	74	289	74	289	74	289	74	289
0.014	87	318	100	382	101	392	101	393	101	393	101	393	101	393	101	393
0.016	106	388	128	483	131	504	132	514	132	514	132	514	132	514	132	514
0.018	126	461	158	588	164	623	167	651	167	651	167	651	167	651	167	651
0.020	146	535	188	697	199	746	206	805	206	805	206	805	206	805	206	805
0.025	198	726	268	983	291	1072	323	1251	323	1263	323	1263	323	1263	323	1263
0.030	251	925	351	1283	387	1418	459	1742	467	1827	467	1827	467	1827	467	1827
0.035	305	1119	435	1596	486	1778	606	2266	639	2492	639	2500	639	2500	639	2500
0.040	360	1337	522	1917	587	2151	761	2817	833	3213	839	3286	839	3286	839	3286
0.045	416	1548	610	2246	691	2534	921	3390	1045	3976	1068	4190	1068	4190	1068	4190
0.050	472	1762	700	2581	796	2925	1085	3982	1270	4774	1327	5218	1327	5218	1327	5218
0.060	586	2198	882	3266	1011	3727	1422	5210	1743	6458	1941	7671	1941	7671	1941	7671
0.070	701	2641	1067	3968	1230	4552	1769	6489	2239	8240	2692	10622	2696	10719	2696	10719
0.080	817	3090	1255	4684	1452	5334	2125	7808	2751	10102	3560	13860	3609	14477	3609	14477
0.090	935	3544	1445	5410	1678	6251	2487	9161	3278	12032	4519	17345	4700	18876	4710	19119
0.100	1053	4002	1637	6146	1906	7121	2856	10543	3818	14021	5549	21056	5954	23705	6023	24495
mm	micrometers															
0.020	0.02	0.06	0.02	0.06	0.02	0.06	0.02	0.06	0.02	0.06	0.02	0.06	0.02	0.06	0.02	0.06
0.040	0.06	0.25	0.06	0.25	0.06	0.25	0.06	0.25	0.06	0.25	0.06	0.25	0.06	0.25	0.06	0.25
0.060	0.14	0.56	0.14	0.56	0.14	0.56	0.14	0.56	0.14	0.56	0.14	0.56	0.14	0.56	0.14	0.56
0.080	0.28	1.0	0.28	1.0	0.28	1.0	0.28	1.0	0.28	1.0	0.28	1.0	0.28	1.0	0.28	1.0
0.100	0.40	1.5	0.40	1.6	0.40	1.6	0.40	1.6	0.40	1.6	0.40	1.6	0.40	1.6	0.40	1.6
0.120	0.56	2.1	0.56	2.3	0.56	2.3	0.56	2.3	0.56	2.3	0.56	2.3	0.56	2.3	0.56	2.3
0.140	0.74	2.8	0.79	3.1	0.79	3.1	0.79	3.1	0.79	3.1	0.79	3.1	0.79	3.1	0.79	3.1
0.160	0.93	3.4	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0
0.180	1.1	4.1	1.3	4.9	1.3	5.1	1.3	5.1	1.3	5.1	1.3	5.1	1.3	5.1	1.3	5.1
0.200	1.3	4.8	1.6	5.9	1.6	6.3	1.6	6.3	1.6	6.3	1.6	6.3	1.6	6.3	1.6	6.3
0.250	1.8	6.8	2.3	8.8	2.4	9.2	2.5	9.8	2.5	9.8	2.5	9.8	2.5	9.8	2.5	9.8
0.300	2.3	8.5	3.1	11.	3.3	12.	3.5	14.	3.6	14.	3.6	14.	3.6	14.	3.6	14.
0.350	2.8	10.	3.9	14.	4.1	15.	4.5	17.	4.8	18.	5.0	19.	5.0	19.	5.0	19.
0.400	3.4	12.	4.6	17.	4.9	18.	5.4	21.	5.7	22.	6.5	25.	6.5	25.	6.5	25.
0.450	3.9	14.	5.3	20.	5.7	21.	6.4	25.	6.7	26.	8.3	32.	8.3	32.	8.3	32.
0.500	4.5	17.	6.0	23.	6.5	24.	7.3	28.	7.6	30.	10.	40.	10.	40.	10.	40.
0.600	5.6	21.	7.2	28.	7.8	30.	8.9	35.	9.3	36.	15.	58.	15.	58.	15.	58.
0.700	6.7	25.	8.5	33.	9.2	35.	10.	41.	11.	42.	20.	81.	20.	81.	20.	81.
0.800	7.9	30.	9.8	38.	10.	40.	12.	47.	12.	48.	27.	107.	27.	107.	27.	107.
1.000	10.	38.	12.	48.	13.	50.	15.	59.	15.	60.	44.	176.	44.	176.	44.	176.
1.200	13.	46.	14.	57.	15.	60.	18.	71.	18.	72.	66.	264.	66.	264.	66.	270.
1.500	16.	61.	18.	73.	19.	76.	23.	90.	23.	91.	99.	396.	99.	396.	112.	449.

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TABLE 18.2–14 THEORETICAL Values for Arithmetic-Average Roughness (R_a) and Maximum Peak-to-Valley Roughness Height (R_t) for Turning or Milling—Tool Type C

TOOL NOSE RADIUS = 0.125 in [1.2 mm]

FEED / REV (Turning) Or FEED / TOOTH (Milling)	3° ECEA		5° ECEA		6° ECEA		10° ECEA		15° ECEA		30° ECEA		40° ECEA		45° ECEA	
	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t
in	microinches															
0.001	0.26	1.0	0.26	1.0	0.26	1.0	0.26	1.0	0.26	1.0	0.26	1.0	0.26	1.0	0.26	1.0
0.002	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0
0.003	2.3	9.0	2.3	9.0	2.3	9.0	2.3	9.0	2.3	9.0	2.3	9.0	2.3	9.0	2.3	9.0
0.004	4.1	16	4.1	16	4.1	16	4.1	16	4.1	16	4.1	16	4.1	16	4.1	16
0.005	6.4	25	6.4	25	6.4	25	6.4	25	6.4	25	6.4	25	6.4	25	6.4	25
0.006	9.2	36	9.2	36	9.2	36	9.2	36	9.2	36	9.2	36	9.2	36	9.2	36
0.007	13	49	13	49	13	49	13	49	13	49	13	49	13	49	13	49
0.008	16	64	16	64	16	64	16	64	16	64	16	64	16	64	16	64
0.009	21	81	21	81	21	81	21	81	21	81	21	81	21	81	21	81
0.010	26	100	26	100	26	100	26	100	26	100	26	100	26	100	26	100
0.012	37	144	37	144	37	144	37	144	37	144	37	144	37	144	37	144
0.014	50	196	50	196	50	196	50	196	50	196	50	196	50	196	50	196
0.016	66	252	66	256	66	256	66	256	66	256	66	256	66	256	66	256
0.018	82	310	83	324	83	324	83	324	83	324	83	324	83	324	83	324
0.020	99	372	103	401	103	401	103	401	103	401	103	401	103	401	103	401
0.025	145	534	160	621	161	627	161	627	161	627	161	627	161	627	161	627
0.030	192	706	228	864	231	895	232	903	232	903	232	903	232	903	232	903
0.035	242	885	301	1122	311	1185	316	1231	316	1231	316	1231	316	1231	316	1231
0.040	292	1070	377	1394	398	1492	413	1610	413	1610	413	1610	413	1610	413	1610
0.045	343	1259	456	1675	488	1812	523	2040	523	2042	523	2042	523	2042	523	2042
0.050	396	1453	536	1965	581	2144	645	2501	647	2526	647	2526	647	2526	647	2526
0.060	502	1850	701	2567	773	2835	917	3484	935	3653	935	3653	935	3653	935	3653
0.070	610	2258	871	3191	971	3557	1213	4533	1277	4984	1278	5000	1278	5000	1278	5000
0.080	720	2673	1044	3834	1174	4303	1523	5635	1667	6426	1677	6573	1677	6573	1677	6573
0.090	831	3096	1221	4491	1381	5068	1843	6781	2091	7951	2135	8381	2135	8381	2135	8381
0.100	944	3525	1399	5161	1592	5850	2170	7963	2539	9547	2654	10436	2654	10436	2654	10436
mm	micrometers															
0.020	0.01	0.04	0.01	0.04	0.01	0.04	0.01	0.04	0.01	0.04	0.01	0.04	0.01	0.04	0.01	0.04
0.040	0.04	0.17	0.04	0.17	0.04	0.17	0.04	0.17	0.04	0.17	0.04	0.17	0.04	0.17	0.04	0.17
0.060	0.10	0.38	0.10	0.38	0.10	0.38	0.10	0.38	0.10	0.38	0.10	0.38	0.10	0.38	0.10	0.38
0.080	0.17	0.67	0.17	0.67	0.17	0.67	0.17	0.67	0.17	0.67	0.17	0.67	0.17	0.67	0.17	0.67
0.100	0.27	1.0	0.27	1.0	0.27	1.0	0.27	1.0	0.27	1.0	0.27	1.0	0.27	1.0	0.27	1.0
0.120	0.39	1.5	0.39	1.5	0.39	1.5	0.39	1.5	0.39	1.5	0.39	1.5	0.39	1.5	0.39	1.5
0.140	0.52	2.0	0.52	2.0	0.52	2.0	0.52	2.0	0.52	2.0	0.52	2.0	0.52	2.0	0.52	2.0
0.160	0.68	2.6	0.68	2.7	0.68	2.7	0.68	2.7	0.68	2.7	0.68	2.7	0.68	2.7	0.68	2.7
0.180	0.85	3.2	0.87	3.4	0.87	3.4	0.87	3.4	0.87	3.4	0.87	3.4	0.87	3.4	0.87	3.4
0.200	1.0	3.8	1.1	4.2	1.1	4.2	1.1	4.2	1.1	4.2	1.1	4.2	1.1	4.2	1.1	4.2
0.250	1.5	5.5	1.7	6.4	1.7	6.5	1.7	6.5	1.7	6.5	1.7	6.5	1.7	6.5	1.7	6.5
0.300	2.0	7.2	2.4	8.9	2.4	9.3	2.4	9.4	2.4	9.4	2.4	9.4	2.4	9.4	2.4	9.4
0.350	2.5	9.0	3.1	12.	3.2	12.	3.3	13.	3.3	13.	3.3	13.	3.3	13.	3.3	13.
0.400	3.0	11.	3.9	14.	4.1	15.	4.3	17.	4.3	17.	4.3	17.	4.3	17.	4.3	17.
0.450	3.5	13.	4.7	17.	5.0	19.	5.4	21.	5.5	21.	5.5	21.	5.5	21.	5.5	21.
0.500	4.0	15.	5.5	20.	6.0	22.	6.7	26.	6.7	26.	6.7	26.	6.7	26.	6.7	26.
0.600	5.1	19.	7.1	26.	7.9	29.	9.5	36.	9.7	38.	9.7	38.	9.7	38.	9.7	38.
0.700	6.2	23.	8.8	32.	9.9	36.	13.	42.	13.	52.	13.	52.	13.	52.	13.	52.
0.800	7.3	27.	11.	39.	12.	44.	16.	56.	17.	66.	18.	69.	18.	69.	18.	69.
1.000	9.5	36.	14.	52.	16.	59.	22.	81.	26.	98.	28.	109.	28.	109.	28.	109.
1.200	12.	44.	18.	66.	20.	75.	29.	106.	36.	132.	41.	161.	41.	161.	41.	161.
1.500	15.	58.	23.	87.	27.	101.	40.	146.	51.	187.	65.	254.	66.	263.	66.	263.
2.000	21.	81.	33.	124.	38.	144.	58.	214.	76.	285.	115.	436.	125.	496.	127.	517.

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TABLE 18.2–15 THEORETICAL Values for Arithmetic-Average Roughness (R_a) and Maximum Peak-to-Valley Roughness Height (R_t) for Turning or Milling—Tool Type C

TOOL NOSE RADIUS = 0.188 in [1.6 mm]																
FEED/REV. (Turning Or FEED/TOOTH (Milling)	3° ECEA		5° ECEA		6° ECEA		10° ECEA		15° ECEA		30° ECEA		40° ECEA		45° ECEA	
	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t
in	microinches															
0.001	0.06	0.67	0.06	0.67	0.06	0.67	0.06	0.67	0.06	0.67	0.06	0.67	0.06	0.67	0.06	0.67
0.002	0.62	2.7	0.62	2.7	0.62	2.7	0.62	2.7	0.62	2.7	0.62	2.7	0.62	2.7	0.62	2.7
0.003	1.5	6.0	1.5	6.0	1.5	6.0	1.5	6.0	1.5	6.0	1.5	6.0	1.5	6.0	1.5	6.0
0.004	2.7	11.	2.7	11.	2.7	11.	2.7	11.	2.7	11.	2.7	11.	2.7	11.	2.7	11.
0.005	4.3	17.	4.3	17.	4.3	17.	4.3	17.	4.3	17.	4.3	17.	4.3	17.	4.3	17.
0.006	6.2	24.	6.2	24.	6.2	24.	6.2	24.	6.2	24.	6.2	24.	6.2	24.	6.2	24.
0.007	8.4	33.	8.4	33.	8.4	33.	8.4	33.	8.4	33.	8.4	33.	8.4	33.	8.4	33.
0.008	11.	43.	11.	43.	11.	43.	11.	43.	11.	43.	11.	43.	11.	43.	11.	43.
0.009	14.	54.	14.	54.	14.	54.	14.	54.	14.	54.	14.	54.	14.	54.	14.	54.
0.010	17.	67.	17.	67.	17.	67.	17.	67.	17.	67.	17.	67.	17.	67.	17.	67.
0.012	25.	96.	25.	96.	25.	96.	25.	96.	25.	96.	25.	96.	25.	96.	25.	96.
0.014	34.	131.	34.	131.	34.	131.	34.	131.	34.	131.	34.	131.	34.	131.	34.	131.
0.016	44.	171.	44.	171.	44.	171.	44.	171.	44.	171.	44.	171.	44.	171.	44.	171.
0.018	55.	216.	55.	216.	55.	216.	55.	216.	55.	216.	55.	216.	55.	216.	55.	216.
0.020	68.	267.	68.	267.	68.	267.	68.	267.	68.	267.	68.	267.	68.	267.	68.	267.
0.025	106.	409.	107.	417.	107.	417.	107.	417.	107.	417.	107.	417.	107.	417.	107.	417.
0.030	149.	583.	154.	601.	154.	601.	154.	601.	154.	601.	154.	601.	154.	601.	154.	601.
0.035	194.	758.	210.	817.	210.	818.	210.	818.	210.	818.	210.	818.	210.	818.	210.	818.
0.040	241.	885.	274.	1050.	274.	1069.	274.	1070.	274.	1070.	274.	1070.	274.	1070.	274.	1070.
0.045	289.	1053.	341.	1296.	347.	1343.	347.	1355.	347.	1355.	347.	1355.	347.	1355.	347.	1355.
0.050	338.	1236.	414.	1552.	426.	1630.	429.	1674.	429.	1674.	429.	1674.	429.	1674.	429.	1674.
0.060	438.	1601.	565.	2090.	596.	2238.	619.	2416.	619.	2416.	619.	2416.	619.	2416.	619.	2416.
0.070	541.	1985.	723.	2656.	778.	2882.	844.	3287.	844.	3296.	844.	3296.	844.	3296.	844.	3296.
0.080	646.	2379.	886.	3244.	966.	3556.	1099.	4230.	1105.	4316.	1105.	4316.	1105.	4316.	1105.	4316.
0.090	753.	2775.	1052.	3850.	1160.	4253.	1376.	5226.	1402.	5480.	1402.	5480.	1402.	5480.	1402.	5480.
0.100	861.	3181.	1221.	4472.	1357.	4970.	1669.	6265.	1736.	6786.	1736.	6790.	1736.	6790.	1736.	6790.
mm	micrometers															
0.020	0.01	0.03	0.01	0.03	0.01	0.03	0.01	0.03	0.01	0.03	0.01	0.03	0.01	0.03	0.01	0.03
0.040	0.03	0.13	0.03	0.13	0.03	0.13	0.03	0.13	0.03	0.13	0.03	0.13	0.03	0.13	0.03	0.13
0.060	0.07	0.28	0.07	0.28	0.07	0.28	0.07	0.28	0.07	0.28	0.07	0.28	0.07	0.28	0.07	0.28
0.080	0.13	0.50	0.13	0.50	0.13	0.50	0.13	0.50	0.13	0.50	0.13	0.50	0.13	0.50	0.13	0.50
0.100	0.20	0.78	0.20	0.78	0.20	0.78	0.20	0.78	0.20	0.78	0.20	0.78	0.20	0.78	0.20	0.78
0.120	0.29	1.1	0.29	1.1	0.29	1.1	0.29	1.1	0.29	1.1	0.29	1.1	0.29	1.1	0.29	1.1
0.140	0.39	1.5	0.39	1.5	0.39	1.5	0.39	1.5	0.39	1.5	0.39	1.5	0.39	1.5	0.39	1.5
0.160	0.51	2.0	0.51	2.0	0.51	2.0	0.51	2.0	0.51	2.0	0.51	2.0	0.51	2.0	0.51	2.0
0.180	0.65	2.5	0.65	2.5	0.65	2.5	0.65	2.5	0.65	2.5	0.65	2.5	0.65	2.5	0.65	2.5
0.200	0.80	3.1	0.80	3.1	0.80	3.1	0.80	3.1	0.80	3.1	0.80	3.1	0.80	3.1	0.80	3.1
0.250	1.2	4.8	1.3	4.9	1.3	4.9	1.3	4.9	1.3	4.9	1.3	4.9	1.3	4.9	1.3	4.9
0.300	1.7	6.2	1.8	7.0	1.8	7.0	1.8	7.0	1.8	7.0	1.8	7.0	1.8	7.0	1.8	7.0
0.350	2.1	7.9	2.4	9.4	2.5	9.6	2.5	9.6	2.5	9.6	2.5	9.6	2.5	9.6	2.5	9.6
0.400	2.6	9.6	3.1	12.	3.2	12.	3.2	13.	3.2	13.	3.2	13.	3.2	13.	3.2	13.
0.450	3.1	11.	3.9	14.	4.0	15.	4.1	16.	4.1	16.	4.1	16.	4.1	16.	4.1	16.
0.500	3.6	13.	4.6	17.	4.9	18.	5.0	20.	5.0	20.	5.0	20.	5.0	20.	5.0	20.
0.600	4.6	17.	6.2	23.	6.7	25.	7.3	28.	7.3	28.	7.3	28.	7.3	28.	7.3	28.
0.700	5.7	21.	7.8	29.	8.6	32.	9.8	38.	9.9	39.	9.9	39.	9.9	39.	9.9	39.
0.800	6.8	25.	9.5	35.	11.	39.	13.	48.	13.	51.	13.	51.	13.	51.	13.	51.
1.000	8.9	33.	13.	48.	15.	53.	19.	69.	20.	79.	20.	80.	20.	80.	20.	80.
1.200	11.	42.	16.	61.	19.	69.	25.	92.	29.	109.	30.	117.	30.	117.	30.	117.
1.500	15.	55.	22.	81.	25.	92.	35.	129.	43.	159.	47.	187.	47.	187.	47.	187.
2.000	20.	77.	31.	116.	36.	134.	53.	193.	68.	250.	87.	339.	88.	351.	88.	351.
2.500	26.	100.	41.	153.	47.	177.	71.	262.	94.	347.	136.	516.	145.	577.	146.	593.

TABLE 18.2-16 THEORETICAL Values for Arithmetic-Average Roughness (R_a) and Maximum Peak-to-Valley Roughness Height (R_t) for Turning or Milling—Tool Type C

TOOL NOSE RADIUS = 0.250 in [2.4 mm]																
FEED/REV. (turning) Or FEED/TOOTH (milling)	3° ECEA		5° ECEA		6° ECEA		10° ECEA		15° ECEA		30° ECEA		40° ECEA		45° ECEA	
	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t
in	microinches															
0.001	0.13	0.50	0.13	0.50	0.13	0.50	0.13	0.50	0.13	0.50	0.13	0.50	0.13	0.50	0.13	0.50
0.002	0.51	2.0	0.51	2.0	0.51	2.0	0.51	2.0	0.51	2.0	0.51	2.0	0.51	2.0	0.51	2.0
0.003	1.2	4.5	1.2	4.5	1.2	4.5	1.2	4.5	1.2	4.5	1.2	4.5	1.2	4.5	1.2	4.5
0.004	2.1	8.0	2.1	8.0	2.1	8.0	2.1	8.0	2.1	8.0	2.1	8.0	2.1	8.0	2.1	8.0
0.005	3.2	13.	3.2	13.	3.2	13.	3.2	13.	3.2	13.	3.2	13.	3.2	13.	3.2	13.
0.006	4.6	18.	4.6	18.	4.6	18.	4.6	18.	4.6	18.	4.6	18.	4.6	18.	4.6	18.
0.007	6.3	25.	6.3	25.	6.3	25.	6.3	25.	6.3	25.	6.3	25.	6.3	25.	6.3	25.
0.008	8.2	32.	8.2	32.	8.2	32.	8.2	32.	8.2	32.	8.2	32.	8.2	32.	8.2	32.
0.009	10.	41.	10.	41.	10.	41.	10.	41.	10.	41.	10.	41.	10.	41.	10.	41.
0.010	13.	50.	13.	50.	13.	50.	13.	50.	13.	50.	13.	50.	13.	50.	13.	50.
0.012	18.	72.	18.	72.	18.	72.	18.	72.	18.	72.	18.	72.	18.	72.	18.	72.
0.014	25.	98.	25.	98.	25.	98.	25.	98.	25.	98.	25.	98.	25.	98.	25.	98.
0.016	33.	128.	33.	128.	33.	128.	33.	128.	33.	128.	33.	128.	33.	128.	33.	128.
0.018	42.	162.	42.	162.	42.	162.	42.	162.	42.	162.	42.	162.	42.	162.	42.	162.
0.020	51.	200.	51.	200.	51.	200.	51.	200.	51.	200.	51.	200.	51.	200.	51.	200.
0.025	80.	313.	80.	313.	80.	313.	80.	313.	80.	313.	80.	313.	80.	313.	80.	313.
0.030	115.	446.	116.	450.	116.	450.	116.	450.	116.	450.	116.	450.	116.	450.	116.	450.
0.035	155.	591.	157.	613.	157.	613.	157.	613.	157.	613.	157.	613.	157.	613.	157.	613.
0.040	198.	744.	206.	801.	206.	801.	206.	801.	206.	801.	206.	801.	206.	801.	206.	801.
0.045	243.	903.	260.	1014.	260.	1015.	260.	1015.	260.	1015.	260.	1015.	260.	1015.	260.	1015.
0.050	289.	1068.	321.	1242.	321.	1253.	321.	1253.	321.	1253.	321.	1253.	321.	1253.	321.	1253.
0.060	385.	1411.	455.	1728.	462.	1790.	463.	1807.	463.	1807.	463.	1807.	463.	1807.	463.	1807.
0.070	483.	1769.	601.	2245.	622.	2370.	631.	2462.	631.	2462.	631.	2462.	631.	2462.	631.	2462.
0.080	584.	2139.	754.	2787.	795.	2984.	825.	3221.	825.	3221.	825.	3221.	825.	3221.	825.	3221.
0.090	687.	2519.	911.	3350.	976.	3624.	1046.	4081.	1046.	4083.	1046.	4083.	1046.	4083.	1046.	4083.
0.100	791.	2900.	1072.	3931.	1162.	4288.	1291.	5002.	1293.	5051.	1293.	5051.	1293.	5051.	1293.	5051.
mm	micrometers															
0.020	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02
0.040	0.02	0.08	0.02	0.08	0.02	0.08	0.02	0.08	0.02	0.08	0.02	0.08	0.02	0.08	0.02	0.08
0.060	0.05	0.19	0.05	0.19	0.05	0.19	0.05	0.19	0.05	0.19	0.05	0.19	0.05	0.19	0.05	0.19
0.080	0.09	0.33	0.09	0.33	0.09	0.33	0.09	0.33	0.09	0.33	0.09	0.33	0.09	0.33	0.09	0.33
0.100	0.13	0.52	0.13	0.52	0.13	0.52	0.13	0.52	0.13	0.52	0.13	0.52	0.13	0.52	0.13	0.52
0.120	0.19	0.75	0.19	0.75	0.19	0.75	0.19	0.75	0.19	0.75	0.19	0.75	0.19	0.75	0.19	0.75
0.140	0.26	1.0	0.26	1.0	0.26	1.0	0.26	1.0	0.26	1.0	0.26	1.0	0.26	1.0	0.26	1.0
0.160	0.34	1.3	0.34	1.3	0.34	1.3	0.34	1.3	0.34	1.3	0.34	1.3	0.34	1.3	0.34	1.3
0.180	0.43	1.7	0.43	1.7	0.43	1.7	0.43	1.7	0.43	1.7	0.43	1.7	0.43	1.7	0.43	1.7
0.200	0.53	2.1	0.53	2.1	0.53	2.1	0.53	2.1	0.53	2.1	0.53	2.1	0.53	2.1	0.53	2.1
0.250	0.84	3.3	0.84	3.3	0.84	3.3	0.84	3.3	0.84	3.3	0.84	3.3	0.84	3.3	0.84	3.3
0.300	1.2	4.8	1.2	4.7	1.2	4.7	1.2	4.7	1.2	4.7	1.2	4.7	1.2	4.7	1.2	4.7
0.350	1.6	6.1	1.6	6.4	1.6	6.4	1.6	6.4	1.6	6.4	1.6	6.4	1.6	6.4	1.6	6.4
0.400	2.0	7.6	2.1	8.3	2.1	8.3	2.1	8.3	2.1	8.3	2.1	8.3	2.1	8.3	2.1	8.3
0.450	2.5	9.3	2.7	11.	2.7	11.	2.7	11.	2.7	11.	2.7	11.	2.7	11.	2.7	11.
0.500	3.0	11.	3.3	13.	3.3	13.	3.3	13.	3.3	13.	3.3	13.	3.3	13.	3.3	13.
0.600	3.9	14.	4.7	18.	4.8	19.	4.8	19.	4.8	19.	4.8	19.	4.8	19.	4.8	19.
0.700	4.9	18.	6.2	23.	6.4	24.	6.6	26.	6.6	26.	6.6	26.	6.6	26.	6.6	26.
0.800	5.9	22.	7.7	29.	8.2	31.	8.6	34.	8.6	34.	8.6	34.	8.6	34.	8.6	34.
1.000	8.0	29.	11.	40.	12.	44.	13.	52.	13.	53.	13.	53.	13.	53.	13.	53.
1.200	10.	37.	14.	52.	16.	58.	19.	72.	19.	76.	19.	76.	19.	76.	19.	76.
1.500	13.	50.	19.	71.	22.	80.	26.	104.	31.	118.	31.	120.	31.	120.	31.	120.
2.000	19.	71.	26.	105.	32.	119.	44.	163.	52.	196.	55.	216.	55.	216.	55.	216.
2.500	25.	93.	37.	139.	43.	159.	61.	225.	77.	283.	89.	351.	89.	351.	89.	351.

TABLE 18.2–17 THEORETICAL Values for Arithmetic-Average Roughness (R_a) and Maximum Peak-to-Valley Roughness Height (R_t) for Turning or Milling—Tool Type C

TOOL NOSE RADIUS = 3.0 mm																
FEED/REV. (Turning) Or FEED/TOOTH (Milling)	3° ECEA		5° ECEA		6° ECEA		10° ECEA		15° ECEA		30° ECEA		40° ECEA		45° ECEA	
	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t
mm	micrometers															
0.020	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02
0.040	0.02	0.07	0.02	0.07	0.02	0.07	0.02	0.07	0.02	0.07	0.02	0.07	0.02	0.07	0.02	0.07
0.060	0.04	0.15	0.04	0.15	0.04	0.15	0.04	0.15	0.04	0.15	0.04	0.15	0.04	0.15	0.04	0.15
0.080	0.07	0.27	0.07	0.27	0.07	0.27	0.07	0.27	0.07	0.27	0.07	0.27	0.07	0.27	0.07	0.27
0.100	0.11	0.42	0.11	0.42	0.11	0.42	0.11	0.42	0.11	0.42	0.11	0.42	0.11	0.42	0.11	0.42
0.120	0.15	0.60	0.15	0.60	0.15	0.60	0.15	0.60	0.15	0.60	0.15	0.60	0.15	0.60	0.15	0.60
0.140	0.21	0.82	0.21	0.82	0.21	0.82	0.21	0.82	0.21	0.82	0.21	0.82	0.21	0.82	0.21	0.82
0.160	0.27	1.1	0.27	1.1	0.27	1.1	0.27	1.1	0.27	1.1	0.27	1.1	0.27	1.1	0.27	1.1
0.180	0.35	1.4	0.35	1.4	0.35	1.4	0.35	1.4	0.35	1.4	0.35	1.4	0.35	1.4	0.35	1.4
0.200	0.43	1.7	0.43	1.7	0.43	1.7	0.43	1.7	0.43	1.7	0.43	1.7	0.43	1.7	0.43	1.7
0.250	0.67	2.6	0.67	2.6	0.67	2.6	0.67	2.6	0.67	2.6	0.67	2.6	0.67	2.6	0.67	2.6
0.300	0.96	3.8	0.96	3.8	0.96	3.8	0.96	3.8	0.96	3.8	0.96	3.8	0.96	3.8	0.96	3.8
0.350	1.3	5.1	1.3	5.1	1.3	5.1	1.3	5.1	1.3	5.1	1.3	5.1	1.3	5.1	1.3	5.1
0.400	1.7	6.5	1.7	6.7	1.7	6.7	1.7	6.7	1.7	6.7	1.7	6.7	1.7	6.7	1.7	6.7
0.450	2.1	8.0	2.2	8.4	2.2	8.4	2.2	8.4	2.2	8.4	2.2	8.4	2.2	8.4	2.2	8.4
0.500	2.6	9.6	2.7	10.	2.7	10.	2.7	10.	2.7	10.	2.7	10.	2.7	10.	2.7	10.
0.600	3.5	13.	3.9	15.	3.9	15.	3.9	15.	3.9	15.	3.9	15.	3.9	15.	3.9	15.
0.700	4.4	16.	5.2	20.	5.2	20.	5.3	20.	5.3	20.	5.3	20.	5.3	20.	5.3	20.
0.800	5.4	20.	6.6	25.	6.8	26.	6.9	27.	6.9	27.	6.9	27.	6.9	27.	6.9	27.
1.000	7.4	27.	9.7	36.	10.	38.	11.	42.	11.	42.	11.	42.	11.	42.	11.	42.
1.200	9.5	35.	13.	47.	14.	51.	15.	60.	16.	61.	16.	61.	16.	61.	16.	61.
1.500	13.	47.	18.	65.	20.	72.	24.	90.	24.	95.	24.	95.	24.	95.	24.	95.
2.000	18.	68.	26.	97.	30.	109.	39.	144.	43.	136.	44.	172.	44.	172.	44.	172.
2.500	24.	89.	35.	131.	40.	148.	55.	203.	66.	236.	69.	273.	69.	273.	69.	273.

TABLE 18.2-18 THEORETICAL Values for Arithmetic-Average Roughness (R_a) and Maximum Peak-to-Valley Roughness Height (R_t) for Turning or Milling—Tool Type C

TOOL NOSE RADIUS = 5.0 mm																
FEED/REV. (Turning) Or FEED TOOTH (Milling)	3° ECEA		5° ECEA		6° ECEA		10° ECEA		15° ECEA		30° ECEA		40° ECEA		45° ECEA	
	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t
mm	micrometers															
0.020	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
0.040	0.01	0.04	0.01	0.04	0.01	0.04	0.01	0.04	0.01	0.04	0.01	0.04	0.01	0.04	0.01	0.04
0.060	0.02	0.09	0.02	0.09	0.02	0.09	0.02	0.09	0.02	0.09	0.02	0.09	0.02	0.09	0.02	0.09
0.080	0.04	0.16	0.04	0.16	0.04	0.16	0.04	0.16	0.04	0.16	0.04	0.16	0.04	0.16	0.04	0.16
0.100	0.06	0.25	0.06	0.25	0.06	0.25	0.06	0.25	0.06	0.25	0.06	0.25	0.06	0.25	0.06	0.25
0.120	0.09	0.36	0.09	0.36	0.09	0.36	0.09	0.36	0.09	0.36	0.09	0.36	0.09	0.36	0.09	0.36
0.140	0.13	0.49	0.13	0.49	0.13	0.49	0.13	0.49	0.13	0.49	0.13	0.49	0.13	0.49	0.13	0.49
0.160	0.16	0.64	0.16	0.64	0.16	0.64	0.16	0.64	0.16	0.64	0.16	0.64	0.16	0.64	0.16	0.64
0.180	0.21	0.81	0.21	0.81	0.21	0.81	0.21	0.81	0.21	0.81	0.21	0.81	0.21	0.81	0.21	0.81
0.200	0.26	1.0	0.26	1.0	0.26	1.0	0.26	1.0	0.26	1.0	0.26	1.0	0.26	1.0	0.26	1.0
0.250	0.40	1.6	0.40	1.6	0.40	1.6	0.40	1.6	0.40	1.6	0.40	1.6	0.40	1.6	0.40	1.6
0.300	0.58	2.3	0.58	2.3	0.58	2.3	0.58	2.3	0.58	2.3	0.58	2.3	0.58	2.3	0.58	2.3
0.350	0.79	3.1	0.79	3.1	0.79	3.1	0.79	3.1	0.79	3.1	0.79	3.1	0.79	3.1	0.79	3.1
0.400	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0	1.0	4.0
0.450	1.3	5.1	1.3	5.1	1.3	5.1	1.3	5.1	1.3	5.1	1.3	5.1	1.3	5.1	1.3	5.1
0.500	1.6	6.3	1.6	6.3	1.6	6.3	1.6	6.3	1.6	6.3	1.6	6.3	1.6	6.3	1.6	6.3
0.600	2.3	8.9	2.3	9.0	2.3	9.0	2.3	9.0	2.3	9.0	2.3	9.0	2.3	9.0	2.3	9.0
0.700	3.1	12.	3.1	12.	3.1	12.	3.1	12.	3.1	12.	3.1	12.	3.1	12.	3.1	12.
0.800	4.0	15.	4.1	16.	4.1	16.	4.1	16.	4.1	16.	4.1	16.	4.1	16.	4.1	16.
1.000	5.8	21.	6.4	25.	6.4	25.	6.4	25.	6.4	25.	6.4	25.	6.4	25.	6.4	25.
1.200	7.7	28.	9.1	35.	9.2	36	9.3	36.	9.3	36.	9.3	36.	9.3	36.	9.3	36.
1.500	11.	39.	14.	50.	14.	53.	14.	57.	14.	57.	14.	57.	14.	57.	14.	57.
2.000	16.	58.	21.	79.	23.	86.	26.	100.	26.	101.	26.	101.	26.	101.	26.	101.
2.500	21.	78.	30.	109	33.	121.	40.	150.	41.	159.	41.	159.	41.	159.	41.	159.

TABLE 18.2–19 THEORETICAL Values for Arithmetic-Average Roughness (R_a) and Maximum Peak-to-Valley Roughness Height (R_t) for Turning or Milling—Tool Type C

TOOL NOSE RADIUS = 10.0 mm																
FEED/REV. (Turning) Or FEED/TOOTH (Milling)	3° ECEA		5° ECEA		6° ECEA		10° ECEA		15° ECEA		30° ECEA		40° ECEA		45° ECEA	
	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t	R_a	R_t
mm	micrometers															
0.020	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01
0.040	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02
0.060	0.02	0.05	0.02	0.05	0.02	0.05	0.02	0.05	0.02	0.05	0.02	0.05	0.02	0.05	0.02	0.05
0.080	0.03	0.08	0.03	0.08	0.03	0.08	0.03	0.08	0.03	0.08	0.03	0.08	0.03	0.08	0.03	0.08
0.100	0.03	0.13	0.03	0.13	0.03	0.13	0.03	0.13	0.03	0.13	0.03	0.13	0.03	0.13	0.03	0.13
0.120	0.05	0.18	0.05	0.18	0.05	0.18	0.05	0.18	0.05	0.18	0.05	0.18	0.05	0.18	0.05	0.18
0.140	0.07	0.25	0.07	0.25	0.07	0.25	0.07	0.25	0.07	0.25	0.07	0.25	0.07	0.25	0.07	0.25
0.160	0.08	0.32	0.08	0.32	0.08	0.32	0.08	0.32	0.08	0.32	0.08	0.32	0.08	0.32	0.08	0.32
0.180	0.11	0.41	0.11	0.41	0.11	0.41	0.11	0.41	0.11	0.41	0.11	0.41	0.11	0.41	0.11	0.41
0.200	0.13	0.50	0.13	0.50	0.13	0.50	0.13	0.50	0.13	0.50	0.13	0.50	0.13	0.50	0.13	0.50
0.250	0.20	0.78	0.20	0.78	0.20	0.78	0.20	0.78	0.20	0.78	0.20	0.78	0.20	0.78	0.20	0.78
0.300	0.29	1.1	0.29	1.1	0.29	1.1	0.29	1.1	0.29	1.1	0.29	1.1	0.29	1.1	0.29	1.1
0.350	0.39	1.5	0.39	1.5	0.39	1.5	0.39	1.5	0.39	1.5	0.39	1.5	0.39	1.5	0.39	1.5
0.400	0.51	2.0	0.51	2.0	0.51	2.0	0.51	2.0	0.51	2.0	0.51	2.0	0.51	2.0	0.51	2.0
0.450	0.65	2.5	0.65	2.5	0.65	2.5	0.65	2.5	0.65	2.5	0.65	2.5	0.65	2.5	0.65	2.5
0.500	0.80	3.1	0.80	3.1	0.80	3.1	0.80	3.1	0.80	3.1	0.80	3.1	0.80	3.1	0.80	3.1
0.600	1.2	4.5	1.2	4.5	1.2	4.5	1.2	4.5	1.2	4.5	1.2	4.5	1.2	4.5	1.2	4.5
0.700	1.6	6.1	1.6	6.1	1.6	6.1	1.6	6.1	1.6	6.1	1.6	6.1	1.6	6.1	1.6	6.1
0.800	2.1	8.0	2.1	8.0	2.1	8.0	2.1	8.0	2.1	8.0	2.1	8.0	2.1	8.0	2.1	8.0
1.000	3.2	13.	3.2	13.	3.2	13.	3.2	13.	3.2	13.	3.2	13.	3.2	13.	3.2	13.
1.200	4.6	18.	4.6	18.	4.6	18.	4.6	18.	4.6	18.	4.6	18.	4.6	18.	4.6	18.
1.500	7.1	27.	7.2	28.	7.2	28.	7.2	28.	7.2	28.	7.2	28.	7.2	28.	7.2	28.
2.000	12.	43.	13.	50.	13.	50.	13.	50.	13.	50.	13.	50.	13.	50.	13.	50.
2.500	16.	60.	20.	74.	20.	77.	20.	78.	20.	78.	20.	78.	20.	78.	20.	78.

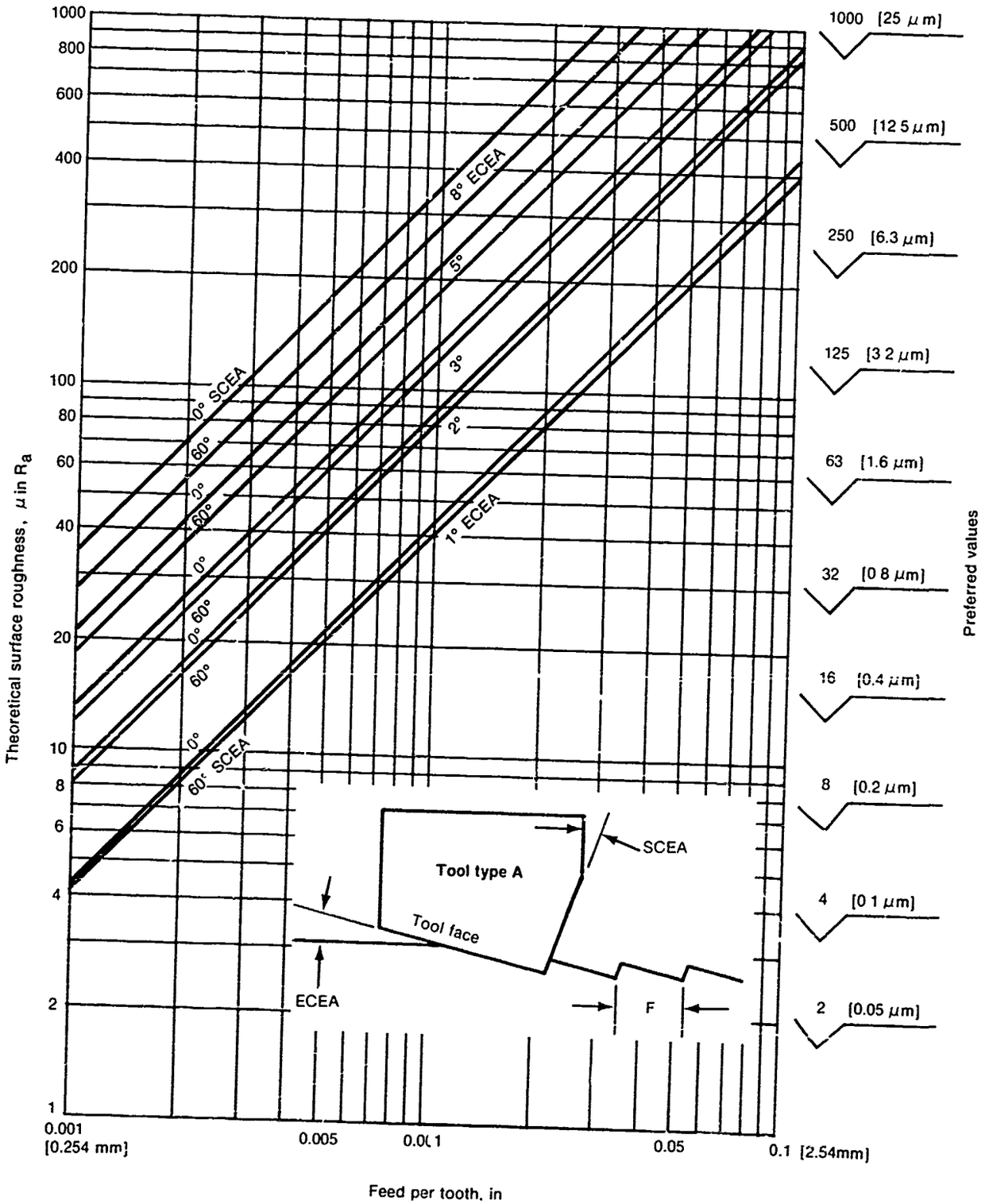


Figure 18.2–14 Theoretical surface roughness for a face milling cutter containing teeth with a zero nose radius.

18.2 Surface Texture

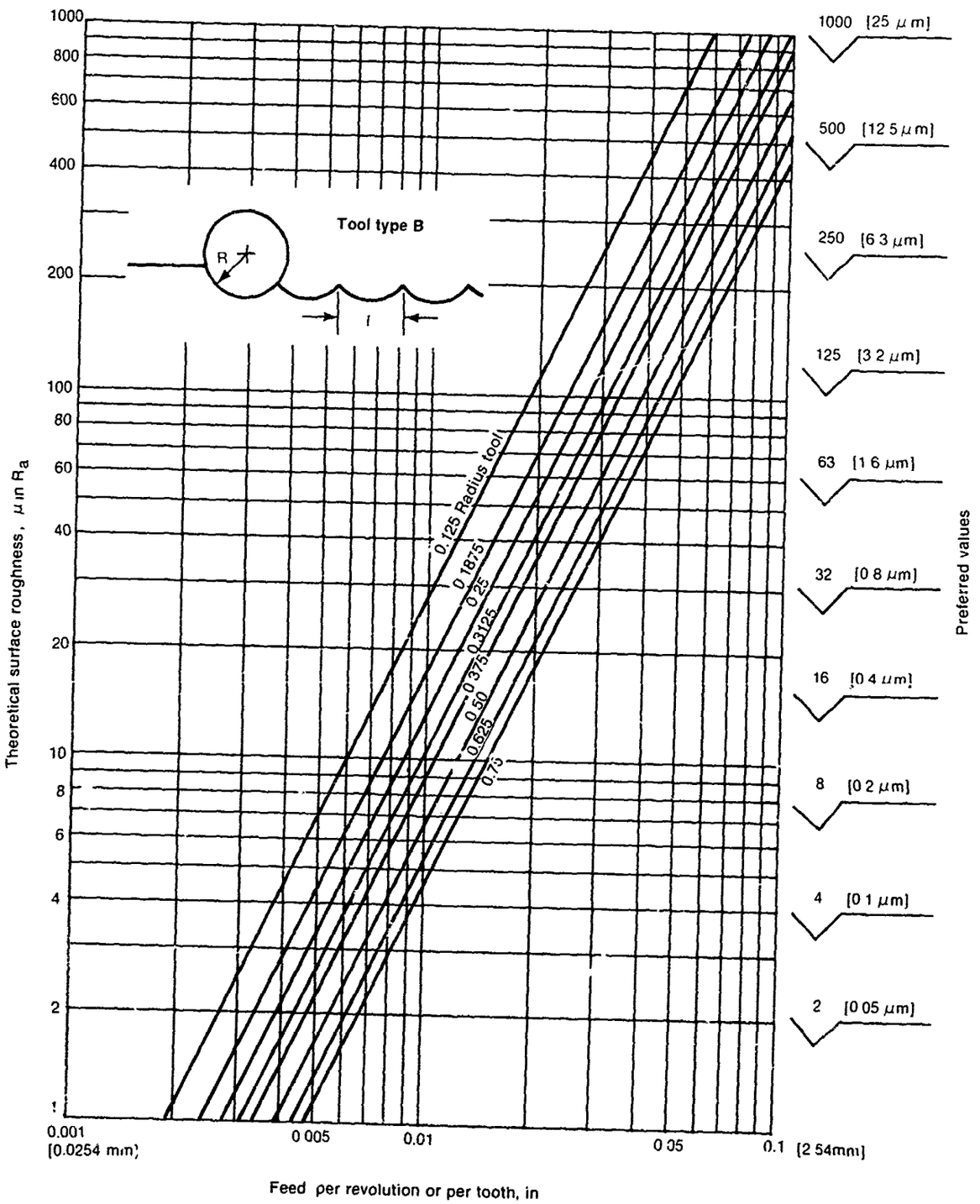


Figure 18.2–15 Theoretical surface roughness for turning or face milling tools with round cutting edges.

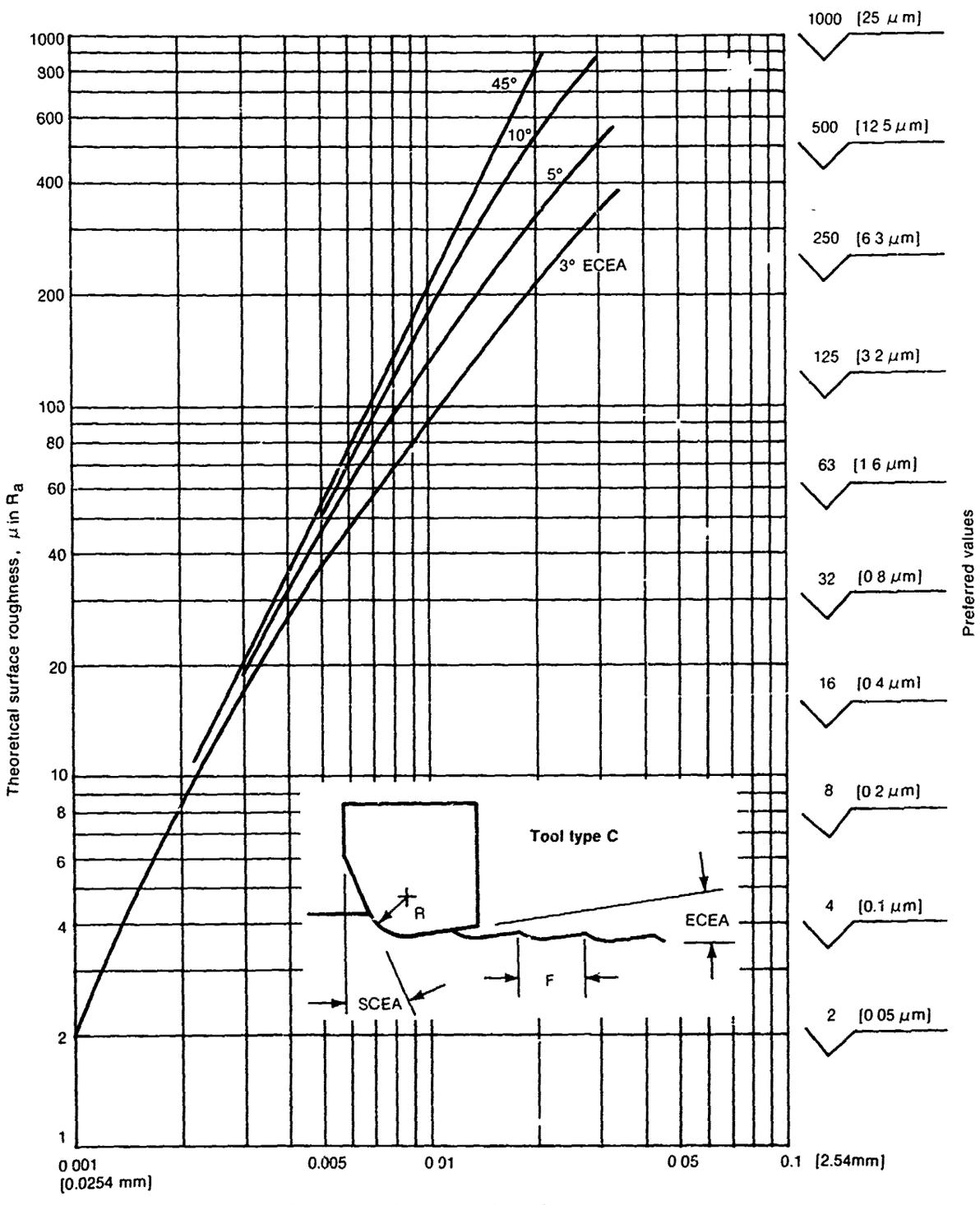


Figure 18.2–16 Theoretical surface roughness for turning or face milling tools with a radius of 0.0156 inch [0.39 mm] and various ECEA.

18.2 Surface Texture

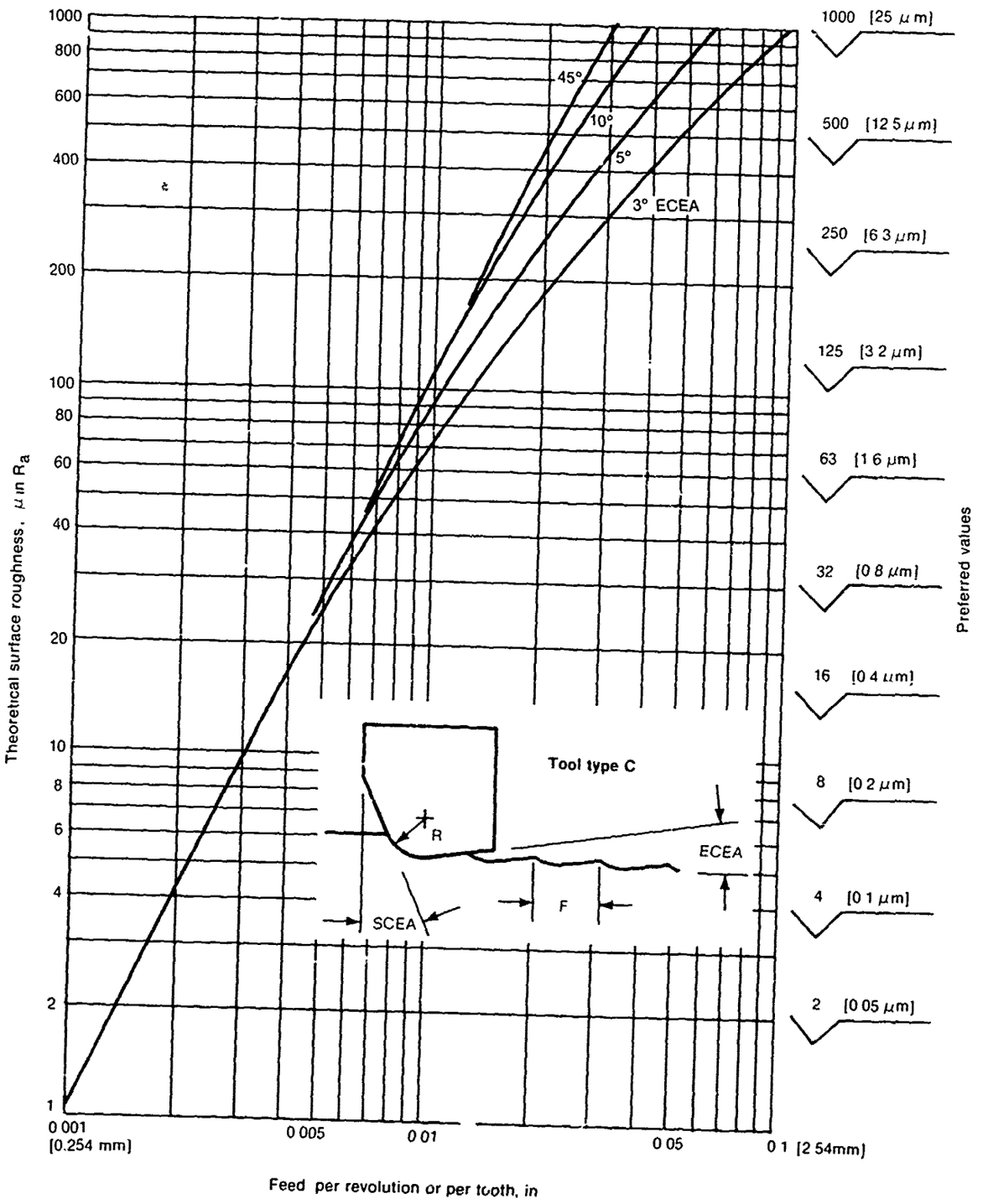


Figure 18.2–17 Theoretical surface roughness for turning or face milling tools with a radius of 0.0312 inch [0.79 mm] and various ECEA.

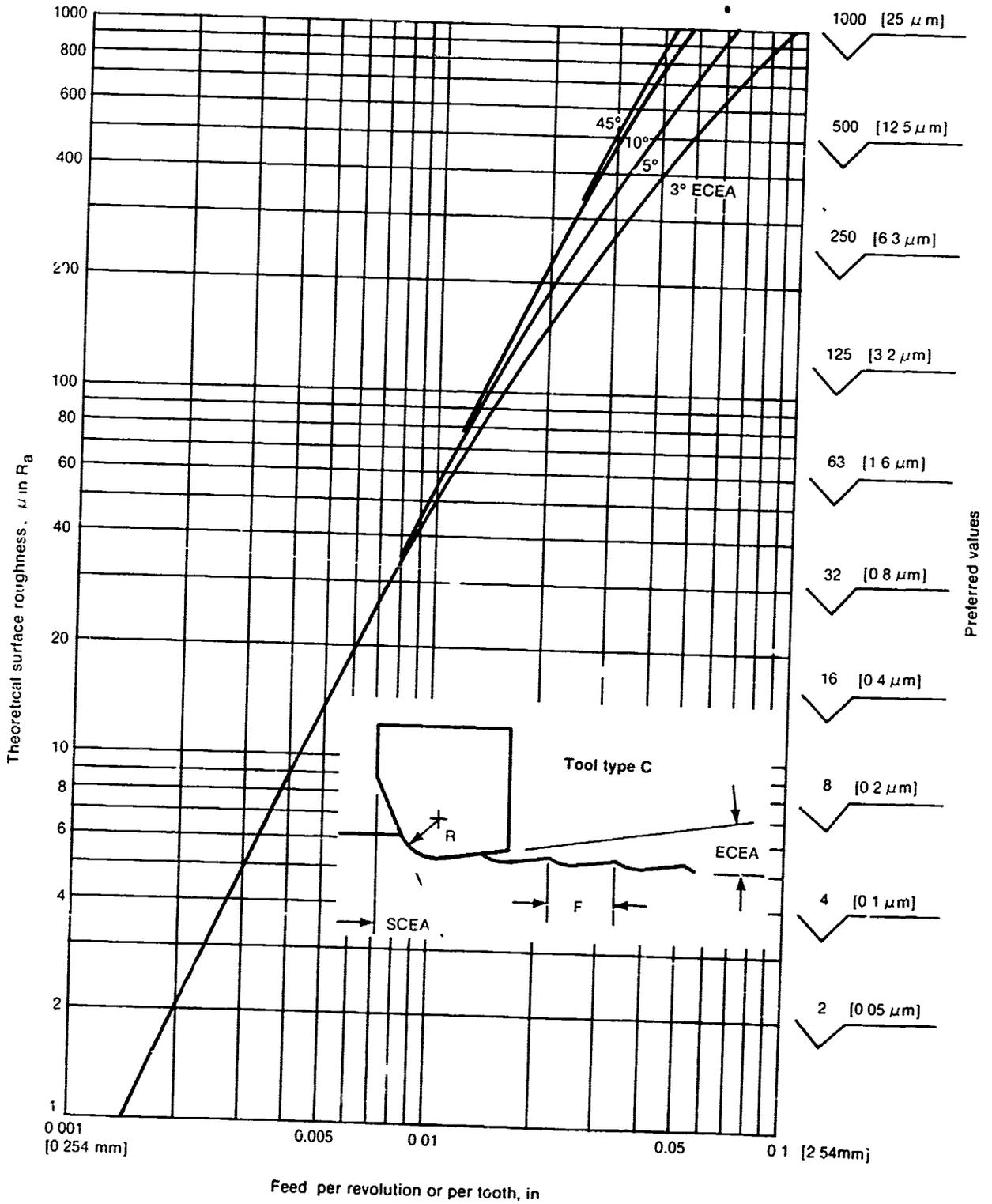


Figure 18.2-18 Theoretical surface roughness for turning or face milling tools with a radius of 0.0625 inch [1.59 mm] and various ECEA.

18.2 Surface Texture

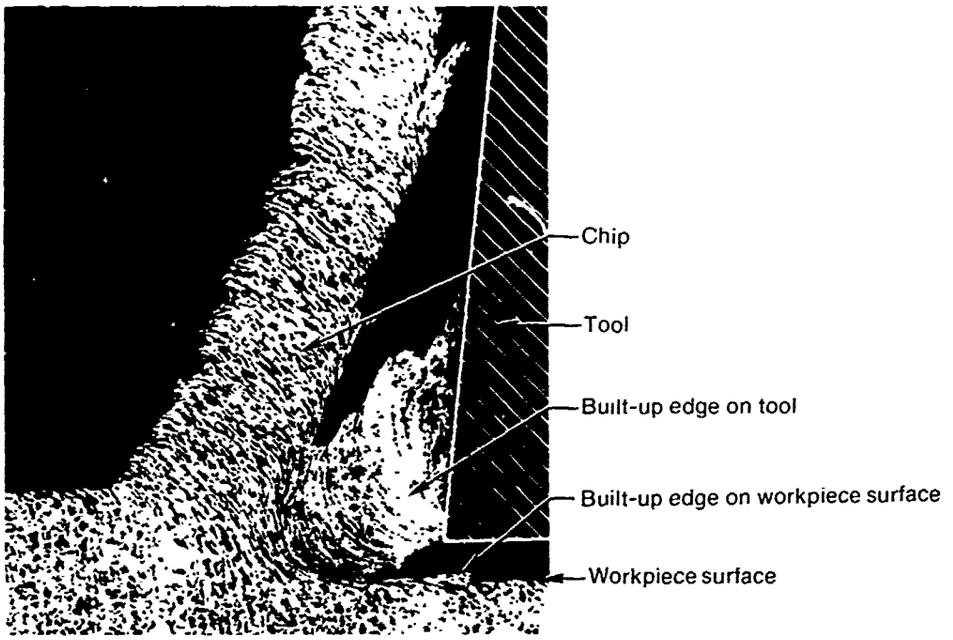


Figure 18.2–19 Built-up edge retained on workpiece surface as detrimental to good surface texture. (Photo from A. J. Pekelharing, *Annals of the CIRP* 23(2): 207.)

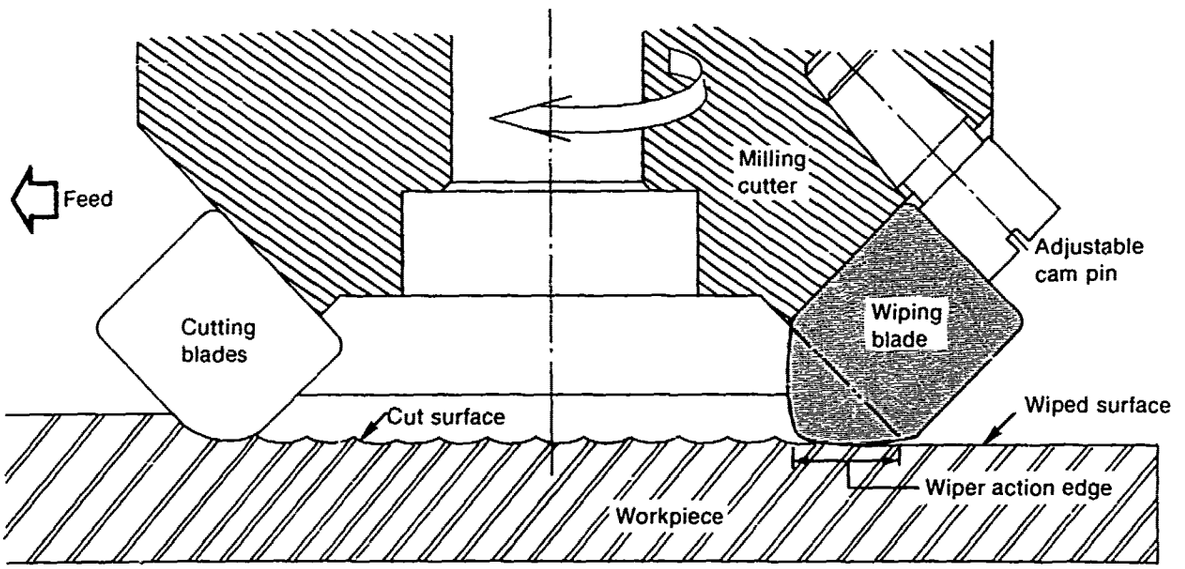


Figure 18.2–20 Wiper blade or micro-finish blade for smoothing feed marks from face milling.

INTRODUCTION

Definitions

The specification and manufacture of unimpaired or enhanced surfaces requires an understanding of the interrelationship of metallurgy, machinability and mechanical testing. To satisfy this requirement, an encompassing discipline known as surface integrity was introduced and has gained worldwide acceptance Surface integrity is the description and control of the many possible alterations produced in a surface layer during manufacturing, including their effects on the material properties and the performance of the surface in service. Surface integrity is achieved by the selection and control of manufacturing processes according to the evaluation of the process effects on significant engineering properties of work materials

For highly stressed, critically loaded or specially engineered surfaces, surface integrity is an added requirement. It is the assessment of the overall engineering quality of a surface and its ability to perform required service functions. It joins dimensions, tolerances and surface texture as an essential specification for highly engineered components in order for them to satisfy modern concerns with safety, product reliability and life cycle costs.

Dynamic loading is recognized as an important factor in the design of many engineering structures in all types of applications. Where dynamic loading is present, operating stresses frequently are limited by the fatigue characteristics of the structural material to be used. Service histories and failure analyses of dynamically loaded components illustrate clearly that fatigue failures often initiate at or just below the surface of a component. Thus, it may be concluded that fatigue behavior is sensitive to surface conditions. Also, in considering stress corrosion resistance, it is recognized that the surface condition of a component is a primary factor in determining susceptibility to attack and possible subsequent part failure.

While all manufacturing processes may have significant effects on the workpiece material and its properties, the bulk of currently available data relates to conventional and nontraditional material removal processes.

Benefits from the Application of Surface Integrity Practices

The disciplined use of surface integrity practices for the manufacture of surfaces which are highly stressed and/or critically loaded can yield significant benefits as follows:

- Enhanced component integrity with resultant increase in safety and service life and decrease in maintenance costs
- Better understanding of the effects of manufacturing process parameters as they relate to reliability of components
- Decreased costs achieved by limiting surface integrity processing only to highly stressed surfaces and simultaneously relaxing costly specification requirements for generating the other surfaces of a component
- Reduction in manufacturing scrap or rework
- Improved process control and quality control through understanding of effects from process control limits
- Better producibility definition
- Strengthened value analysis
- Better defined manufacturing and/or design leeways
- Guidance to advanced process design or application
- More disciplined process selection

Problems Amenable to Surface Integrity Discipline

Before applying surface integrity technology, one must first decide whether a surface integrity problem actually exists. The control of surface integrity generally adds cost to the manufacturing process; therefore, surface integrity should not be a consideration unless a problem exists or may be considered as a possibility. Surface integrity must be considered in the manufacture of highly stressed components used in applications involving human safety, high cost, and predictable component life. If a surface integrity problem exists, then the pertinent surface characteristics and the affected engineering properties of the material must be monitored. Some examples of the types of problems for which the application of surface integrity principles can be helpful are as follows:

- *overheating or burning*: grinding burns on high strength alloys; for example, gears, landing gear cylinders, bearings, turbine blades—see figure 18.3-1
- *microcracks* and *surface irregularities* as initiation sites for failures
- *distortion* and loss of dimensional quality, particularly in thin components
- *residual stresses* lowering fatigue endurance strength
- *residual stresses* combined with severe environments leading to early stress corrosion failures
- *reduction in fatigue strength* from metallurgically altered surfaces; for example, untempered or overtempered martensite, recast or resolidifed areas from thermal processes
- *metallurgical or mechanical alterations* produced as a result of excessively high removal rates or process energy
- *thin sections* of components operating at high stress levels
- applications where *life or safety reliability concerns* are particularly stringent
- holes with *high depth-to-diameter ratios* where maintaining drill sharpness may be difficult

18.3 Surface Integrity

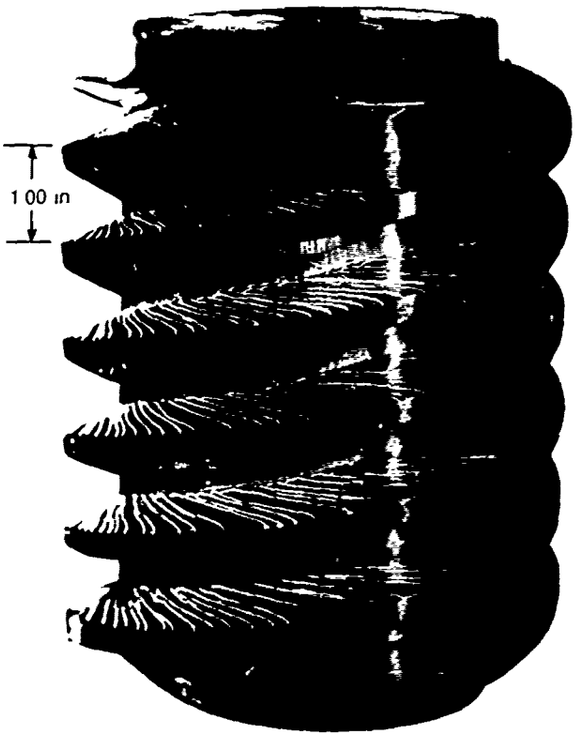


Figure 18.3–1 Failure in grinding of a carburized 8620 steel worm gear; an absence of surface integrity from leading edge dullness on plunge gear grinding. Ultraviolet light photograph of fluorescent penetrant indications found during inspection after grinding. (G. Bellows[13])

A practical balance must be found between over-controlling the manufacturing process with its attendant costs and unneeded benefits and under-controlling with its possible decrease in quality, increase in scrapped components, or loss of reliability. Good application of surface integrity practices can result in cost improvement and quality enhancement by insisting on greater surface quality only on surface areas where needed and relaxing specifications for the bulk of the component surfaces.

ALTERED MATERIAL ZONES (AMZ)

Surface integrity is concerned primarily with the host of effects a manufacturing process produces below the visible surface. The subsurface characteristics occur in various layers or zones. The subsurface altered material zones (AMZ) can be as simple as a stress condition different from that in the body of the material or as complex as a microstructure change interlaced with intergranular attack (IGA). Changes can be caused by chemical, thermal, electrical, or mechanical energy and may affect both the physical and the metallurgical properties of the material. The principal causes of alterations to a surface during material removal operations are as follows:

- high temperatures and high temperature gradients
- plastic deformation or mechanical strain
- chemical reactions or absorption on nascent machined surfaces
- excessive electrical currents
- excessive energy densities during processing

The subsurface altered material zones can be grouped by the principal energy modes that produce them, as shown in table 18.3-1. Table 18.3-2 lists alterations that have been observed in several classes of materials as a result of various machining processes.

TABLE 18.3-1 Altered Material Zones by Principal Energy Mode

MECHANICAL:
- Plastic deformations (as result of hot or cold working)
- Tears and laps and crevice-like defects (associated with "built-up edge" produced in machining)
- Hardness alterations
- Cracks (macroscopic and microscopic)
- Residual stress distribution in surface layer
- Processing inclusions introduced
- Plastically deformed debris as a result of grinding
- Voids, pits, burrs or foreign material inclusions in surface

METALLURGICAL:
- Transformation of phases
- Grain size and distribution
- Precipitate size and distribution
- Foreign inclusions in material
- Twinning
- Recrystallization
- Untempered martensite (UTM) or overtempered martensite (OTM)
- Resolutioning or austenite reversion

CHEMICAL:
- Intergranular attack (IGA)
- Intergranular corrosion (IGC)
- Intergranular oxidation (IGO)
- Preferential dissolution of microconstituents
- Contamination
- Embrittlement—by chemical absorption of elements such as hydrogen, chlorine, etc.
- Pits or selective etch
- Corrosion
- Stress corrosion

THERMAL:
- Heat-affected zone (HAZ)
- Recast or redeposited material
- Resolidified material
- Splattered particles or remelted metal deposited on surface

ELECTRICAL:
- Conductivity change
- Magnetic change
- Resistive heating or overheating

SOURCE: G. Bellows and D. N. Tishler.[7]

TABLE 18.3-2 Summary of Possible Surface Alterations Resulting From Various Metal Removal Processes

MATERIAL	CONVENTIONAL METAL REMOVAL METHODS		NONTRADITIONAL REMOVAL METHODS		
	Milling, Drilling, or Turning	Grinding	EDM	ECM	CHM
Steels:					
Nonhardenable 1018	R, PD, L & T	R, PD	R, MCK, RC	R, SE, IGA	R, SE, IGA
Hardenable 4340 D6ac	R, PD, L & T MCK, UTM, OTM	R, PD, MCK, UTM, OTM	R, MCK, RC, UTM, OTM	R, SE, IGA	R, SE, IGA
Tool Steel D2	R, PD, L & T MCK, UTM, OTM	R, PD, MCK, UTM, OTM	R, MCK, RC, UTM, OTM	R, SE, IGA	R, SE, IGA
Stainless (martensitic) 410	R, PD, L & T MCK, UTM, OTM	R, PD, MCK, UTM, OTM	R, MCK, RC, UTM, OTM	R, SE, IGA	R, SE, IGA
Stainless (austenitic) 302	R, PD, L & T	R, PD	R, MCK, RC	R, SE, IGA	R, SE, IGA
Precipitation hardening 17-4 PH	R, PD, L & T, OA	R, PD, OA	R, MCK, RC, OA	R, SE, IGA	R, SE, IGA
Maraging (18% Ni) 250 Grade	R, PD, L & T, RS, OA	R, PD, RS, OA	R, RC, RS, OA	R, SE, IGA	R, SE, IGA
Nickel and Cobalt Base Alloys: Inconel alloy 718, Rene 41 HS 31 IN-100	R, PD, L & T, MCK	R, PD, MCK	R, MCK, RC	R, SE, IGA	R, SE, IGA
Titanium Alloy: Ti-6Al-4V	R, PD, L & T	R, PD, MCK	R, MCK RC	R, SE, IGA	R, SE
Refractory Alloys: TZM	R, L & T, MCK	R, MCK	R, MCK	R, SE, IGA	R, SE
Tungsten (pressed and sintered)	R, L & T, MCK	R, MCK	R, MCK	R, SE, MCK, IGA	R, SE, MCK, IGA

SOURCE: M. Field, J. F. Kahles and J. T. Cammett [7]

Key R — Roughness of surface
PD — Plastic deformation and plastically deformed debris
L & T — Laps and tears and crevice-like defects
MCK — Microcracks
SE — Selective etch
IGA — Intergranular attack
UTM — Untempered martensite
OTM — Overtempered martensite
OA — Overaging
RS — Resolution or austenite reversion
RC — Recast, respattered metal, or vapor deposited metal

18.3 Surface Integrity

AMZ Definitions

Cracks are narrow ruptures or separations that alter the continuity of a surface. They are usually tight and characterized by sharp edges or sharp changes in direction with depth-to-width ratio of 4:1 or greater and discernible with the unaided eye or with 10X or less magnification.



Microcracks are those cracks requiring greater than 10X magnification for discernment, as shown in figures 18.3-2 and 18.3-4.

Craters are surface depressions with rough edges, approximately round or oval and shallow, usually with a depth-to-width ratio of less than 4:1. This term is frequently applied to the impressions left by the individual spark discharges in electrical discharge machining (EDM), as shown in figure 18.3-3, but is also used to describe massive depressions resulting from short circuit accidents in EDM or ECM. See also *Pits*.



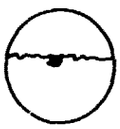
Hardness alterations are changes in hardness of a surface layer as a result of heat, mechanical deformation or chemical change during processing. (Alterations of less than ±2 points Rockwell C or equivalent from the hardness of the bulk of the material are not considered significant.) (See also figure 18.3-15.)



Heat-affected zones (HAZ) are those portions of a material not melted, yet subjected to sufficient thermal energy to produce microstructural alterations or microhardness alterations, as shown in figure 18.3-4.



Inclusions are small particles in the surface layer of an object and may be either foreign or a part of the normal composition of the material, as shown in figure 18.3-4.



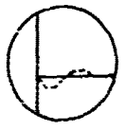
Intergranular attack (IGA) is a form of corrosion or attack in which preferential reactions are concentrated at the surface grain boundaries, usually in the form of sharp notches or discontinuities, as shown in figure 18.3-5. These effects are sometimes supplemented by intergranular oxidation (IGO) derived from exposure to elevated temperatures or intergranular corrosion (IGC) derived from exposure to active chemical reagents.



Laps, folds or seams are defects in a surface from continued plastic working of overlapping surfaces, as shown in figure 18.3-6.



Low stress surface is one containing a residual stress less than 20 ksi [138 MPa] or 10 percent of tensile strength, whichever is greater, at depths below the surface greater than 0.001 inch [0.025 mm]. Sometimes called a stress-free surface.



Metallurgical transformations are those microstructural changes resulting from external influences. They include recrystallization, alloy depletion, chemical reactions, and resolidified or redeposited or recast layers. Figure 18.3-7 shows an example of metallurgical transformation.



Microcracks—See *Cracks*.

Pits are shallow depressions resembling a small crater with rounded edges and less than 4:1 depth-to-width ratio. Also describes a specialized form of localized or selective etching or corrosion that results in holes or pockets left by the mechanical removal of small particles or inclusions from the surface. Pits also are the result of dents from the impingement of foreign particles against the surface. Pits sometimes are associated from electrochemical action into regions slightly removed from the high current density regions. See figure 18.3-8. See also *Craters*.



Plastic deformation is a microstructural change as a result of exceeding the yield point of the material and generally includes elongation of the grain structure and increased hardness. See figure 18.3-9.



Recrystallization is the formation of new, strain-free grain or crystal structure from that existing in the material prior to processing, usually as a result of plastic deformation and subsequent heating or from a phase change occurring during heating. See figure 18.3-10.



Recast material is a general term applied to surfaces that have at some point in the processing become molten and then resolidified. Frequently includes a conglomerate mixture of redeposited or remelted material, as shown in figure 18.3-11.



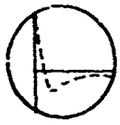
Redeposited material is that material, which in the material removal process, is removed from the surface in a molten state, and then prior to solidification is reattached to the surface. This is sometimes called splattered metal and is also shown in figure 18.3-11.



Remelted or resolidified material is that portion of the surface which during the metal removal process become molten, but is not removed from the surface prior to resolidification. See figure 18.3-11.



Residual stresses are those stresses which are present in a material after all external influences (forces, thermal gradients, or external energy) have been removed. See figure 18.3-16.



Selective etch is a form of in-process corrosion or attack in which preferential reactions are concentrated within and through the grains or concentrated on certain constituents in the base material. See figure 18.3-12.



Splattered metal–See *Redeposited material* and figure 18.3-11.



Figure 18.3-4 Example of heat-affected zone. Laser machining of Inconel Alloy 718 (solution treated and aged). 1000X. Note epitaxial growth of grains nucleating from base metal grains. Also shows microcracks and an inclusion. (Surface integrity Encyclopedia[1])



Figure 18.3-2 Example of microcrack from grinding of Udimet 700C, 250X. (Surface Integrity Encyclopedia[1])

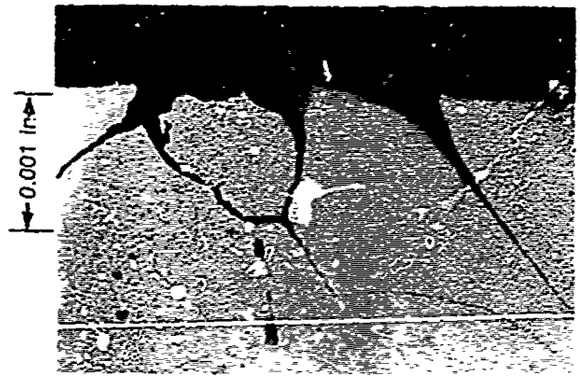


Figure 18.3-5 Example of intergranular attack, ECM of Waspaloy (aged, 40 R_C), 1000X. (W. P. Koster et al[2])

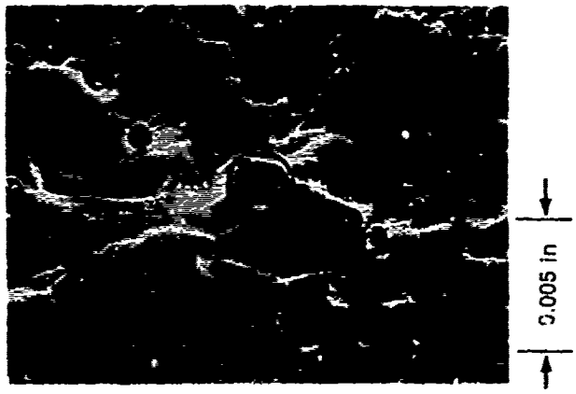


Figure 18.3-3 Example of craters, EDM of Inconel Alloy 718 (solution treated and aged). SEM at 30° and 215X. (Surface Integrity Encyclopedia[1])

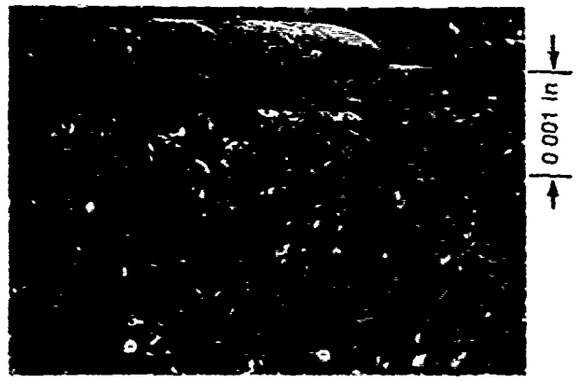


Figure 18.3-6 Example of lap, fold and tears. Drilling of 4340 steel (quenched and tempered, 50 R_C), 1000X perpendicular to lay.

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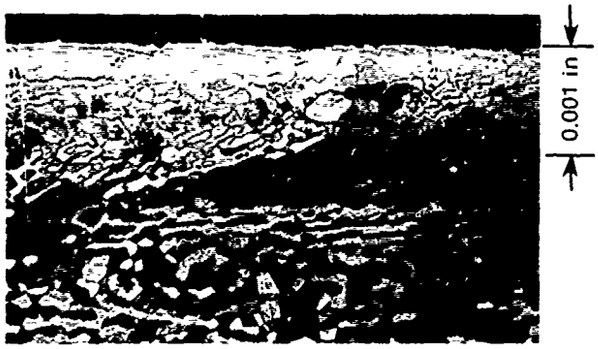


Figure 18.3–7 Example of metallurgical transformation. Reformed alpha case crystals of Ti-6Al-4V during grinding, 1000X. Note also the plastic deformation.



Figure 18.3–9 Example of plastic deformation. Conventional turning of Inconel Alloy 718 (solution treated and aged) with dull tool, 500X, approximately 0.0036-inch deep. (Surface Integrity Encyclopedia[1])

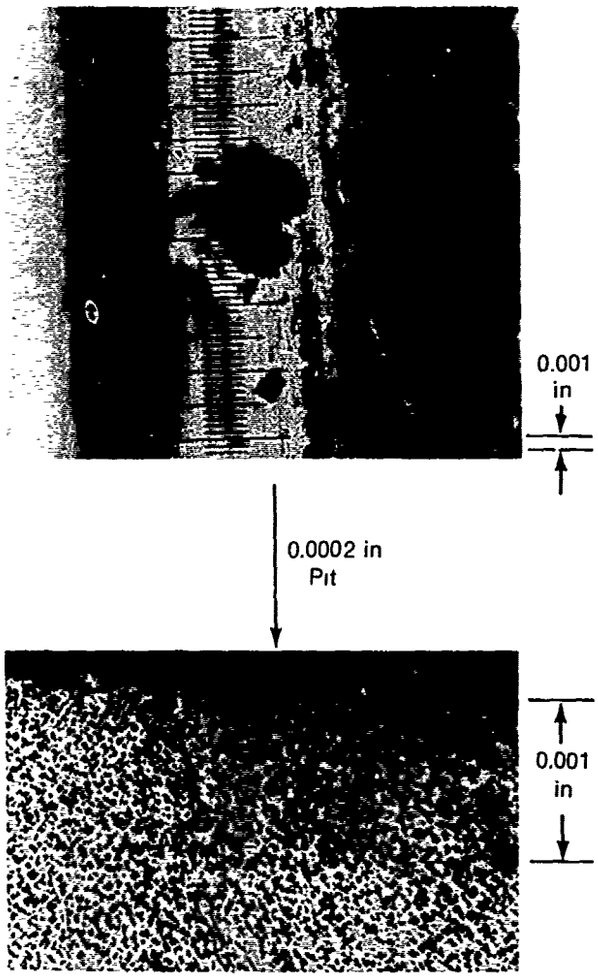


Figure 18.3–8 Example of pit from grinding of Rene 80 (solution treated). *Top*, surface view at 40X; *bottom*, section at 1000X. (Surface Integrity Encyclopedia[1])

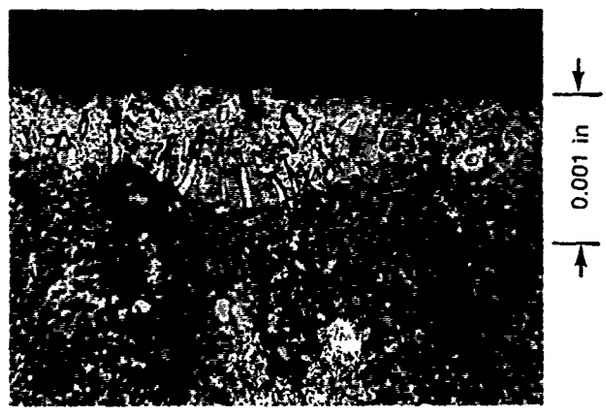


Figure 18.3–10 Example of recrystallization. Recrystallized layer from age heat treatment following grinding of Rene 80, 1000X. (Surface Integrity Encyclopedia[1])



Figure 18.3–11 Example of recast, redeposited and splattered material. EDM of 4340 steel (quenched and tempered 50 R_C), 1000X. Note underlying untempered martensite in the 0.002 inch-deep heat-affected zone. (W. P. Koster et al[8])

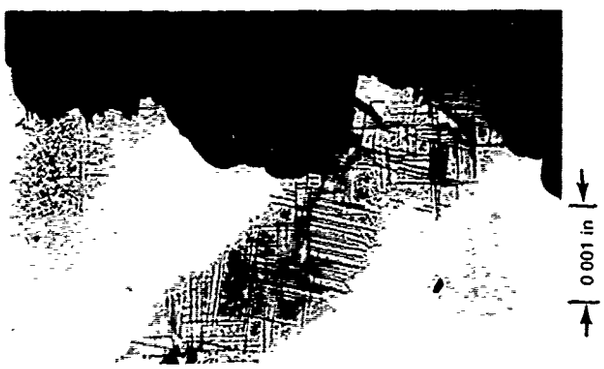


Figure 18.3–12 Example of selective etching. Chemical machining of Inconel Alloy 718C (solution treated and aged, 40 R_C), 1000X. (W. P. Koster et al[8])

EVALUATION TECHNIQUES

Experimental procedures have been developed to provide three increasingly deeper levels of surface integrity evaluation. The *minimum data set* is the least expensive approach and should be considered only as a screening test for the analysis of surface effects. It is essentially metallographic information supplemented with microhardness and surface texture measurements. Table 18.3-3 describes the components of the minimum data set.

The *standard data set* provides more in-depth data for more critical applications. It includes the results from the minimum data set along with residual stress (or distortion) profiles and high cycle fatigue screening tests, as outlined in table 18.3-4. Generally, the standard data set has information at two or more diverse levels of process intensity to represent finishing and roughing (or abusive) machining conditions. Figure 18.3-13 is an example of the standard data set produced in grinding of 4340 steel, quenched and tempered to 50 R_C.

The *extended data set* provides data gathered from statistically designed fatigue programs and yields data suitable for detailed designing. It also includes specialized data such as stress corrosion life with specific types of environmental exposures. Components of the extended data set are given in table 18.3-5.

TABLE 18.3-3 Minimum Surface Integrity Data Set

1. Surface texture
   - roughness measurement (per ANSI B46.1–1978) or microtopographic map (figure 18.2-7, section 18.2)
   - lay designation or photo
2. Macrostructure (10X or less)
   - macrocracks or surface imperfections (pits, laps, etc.)
   - occasionally includes scanning electron microscope (SEM) series of photos at increasing magnifications (recommended series 20, 200, 1000, and 2000X) (figure 18.2-8, section 18.2)
   - macroetch indications (e.g., fluorescent penetrant or magnetic flux or similar)
3. Microstructure (cross section examination at 1000X preferred)
   - microcracks
   - plastic deformation (section parallel to lay suggested)
   - phase transformations
   - intergranular attack
   - micro defects (laps, inclusions, etc.)
   - built-up edge or deposits of debris
   - recast layers
   - selective etching
   - metallurgical transformations
4. Microhardness alterations
   - heat-affected zones

SOURCE: G. Bellows and D. N. Tishler.[25]

TABLE 18.3-4 Standard Surface Integrity Data Set

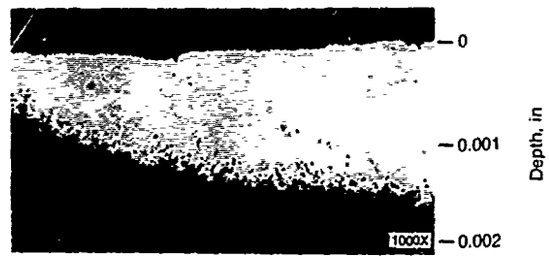
1. Minimum data set
2. Residual stress profile—or distortion measurements
3. Fatigue tests (screening only—recommend using full-reverse bending at room temperature using tapered area flat specimens with results to 10^7 cycles)

SOURCE: G. Bellows and D. N. Tishler.[25]

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LOW STRESS CONDITIONS — No visible surface alterations in microstructure were detected.



ABUSIVE CONDITIONS — A total heat affected zone of 0 013 inch was produced The white layer shown above is 65 R_C and approximately 0.001-0 002 inch deep but in some sections was up to 0 005 inch deep.

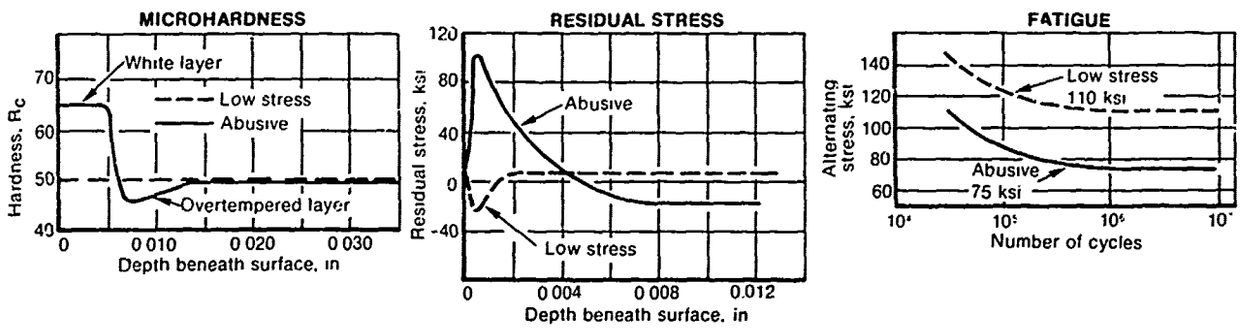


Figure 18.3–13 Surface integrity standard data set for grinding of 4340 steel (quenched and tempered, 50 R_C). Data are for two levels of grinding intensity: low stress and abusive. (W. P. Koster et al[9])

TABLE 18.3-5 Extended Surface Integrity Data Set

1. Standard data set
2. Fatigue tests—statistical data to establish design data
3. Stress corrosion tests at selected environmental conditions
4. Additional mechanical testing
   - tensile
   - stress rupture
   - creep
   - specialized: friction, wear, sealing, bearing performance
   - fracture toughness
   - low cycle fatigue
   - elevated or cryogenic temperature
   - crack propagation
   - surface chemistry

SOURCE: G. Bellows and D. N. Tishler.[25]

Process Intensities and Surface Integrity

Processes are usually operated over a range of intensities. The roughing and finishing modes are one reflection of these differing intensities or energy densities. From a surface integrity and quality assurance standpoint, it is necessary to consider the change in surface effects over the full range of energy levels expected to be used. These data can then be used to establish reasonable quality control limits. This range of process intensity levels is often implied in the machining terminology that indicates increasingly intense processing, such as the following:

- low stress surface
- finish machining (or "gentle")
- conventional (or "standard")
- roughing (or "off standard")
- abusive (or accidental conditions)

The surface integrity of components produced with roughing or off-standard operating conditions is frequently less than that produced under standard conditions. The standard surface integrity data set evaluations should include at least two levels of process intensity. It should be emphasized that ultimately abusive and gentle processing can be differentiated only by mechanical testing (fatigue, stress corrosion, etc.) and/or service performance.

Metallographic Sectioning and Special Preparation Techniques

Microscopic examination is an important and inexpensive means for rapid initial surface integrity evaluation. However, special metallographic techniques are necessary for studying surface phenomena. Surface microstructure alterations are generally very shallow, usually of the order of 0.001 to 0.003 inch [0.025 to 0.076 mm]. Under very abusive conditions, alterations as deep as 0.005 to 0.015 inch [0.127 to 0.38 mm] have been noted. Often significant microstructure alterations, microcracks, or flaws as shallow as 0.0001 inch [0.0025 mm] in depth are developed during material removal processing. Thus, it is necessary to employ sectioning, mounting and other metallographic techniques which do not alter or destroy the pertinent surface and which maintain high edge retention. One successful technique consists of the application of vacuum epoxy mounting as outlined in table 18.3-6 and shown in figure 18.3-14. It should be noted that the frequently employed edge retention technique of plating can alter some of the surface effects that might be present.

Various types of microscopy are available for the evaluation of surface metallurgy including optical microscopy, scanning electron microscopy (SEM), and transmission electron microscopy (TEM). Optical microscopy is the least expensive and the most widely applicable method. It is advisable to examine metallurgical mounts first in the unetched condition, thereby accentuating the profile, microcracks, inclusions, voids, and crevice-like defects. After etching, specimens are reexamined for microstructural identification and grain boundary conditions.

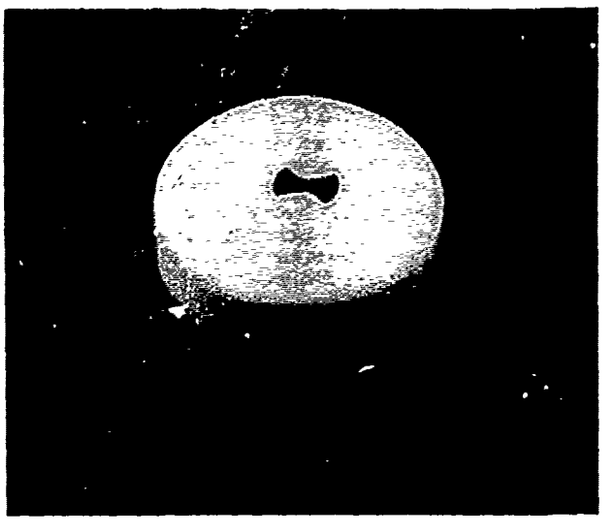


Figure 18.3-14 A 1-1/4 inch diameter metallographic mount prepared by the vacuum epoxy method. The white layer contains aluminum oxide pellets. (M. Field, J. F. Kahles, and J. T. Cammett[12])

Microhardness Determinations

Microhardness determinations can be made on the previously described metallurgical mounts using a microhardness tester with either a Knoop or a Vickers indenter. Microhardness studies are important for identifying the possible overall effects of heat-affected zones caused by specific material removal operations. Examples of surface effects revealed by microhardness variations include the following:

- areas of untempered or overtempered martensite
- softening from resolutioned austenite
- chemical softening (sometimes associated with chemical machining or electrochemical machining)
- heat-affected zones
- plastic deformation or work hardened zones

Figure 18.3-15 illustrates some of the types of hardness alterations observed.

TABLE 18.3-6 Mounting Technique and Metallographic Preparation for Edge Retention

1. Samples are sectioned from the workpiece in a manner which leads to the least possible distortion or burring. Bandsawing or hacksawing is preferred. A minimum of 0.030 inch [0.76 mm] is then removed from the cut surface using a 120-grit silicon carbide paper on a low-speed polisher.
2. Copper molds (or tubes), 1¼ inches [31.8 mm] inside diameter by 2¾ inches [70 mm] high, are placed on a pallet approximately 5 inches [125 mm] in diameter. The inner surface of the molds and surface of the pallet are previously sprayed with a silicone releasing agent.
3. After placing a metallurgical specimen in a mold, a mixture of epoxy resin, hardener, and pelletized aluminum oxide, sufficient to produce a layer of ¼ to ⅜ inch [6.4 to 9.5 mm] in depth, is poured over the specimen. The ratio of resin to hardener is 4 to 1. The amount of pellets added is in the range of 10 to 15 grams. The hardness or abrasive level of the pelletized material used (low, medium, or high fired) is strictly a function of the alloy to be prepared and its hardness characteristics.
4. The pallet containing the molds is placed in a vacuum chamber (at a vacuum of 1 x 10^{-2} to 1 x 10^{-1} torr) in order to degas the mixture, thereby improving the adherence of the epoxy and pellets to the surface of the specimen. When vigorous bubbling of the mixture decreases after vacuum impregnation, sufficient resin and hardener (4 to 1 ratio) is added to produce a mount approximately 1 inch [25 mm] high.
5. The mounts are cured at a temperature not greater than 70°F [21°C] for approximately 10 hours. Casting of the mounts is accomplished during the latter portion of the laboratory workday so that curing occurs overnight.
6. After curing, they are placed in an oven at a temperature of 150°F [66°C] for a period of one hour after which they are removed from the molds.
7. Approximately 0.020 inch [0.50 mm] of stock is then removed from the as-mounted metal surface on a positive positioning automatic polishing unit, using the side of a 1-by-13-inch [25 x 330 mm] aluminum oxide 320-grit grinding wheel as the grinding medium. Water is used as a coolant.
8. Subsequent rough grinding is performed wet on silicon carbide papers or equivalent ranging from 240 to 600 grit.
9. For steels and nickel- and cobalt-base superalloys, the intermediate polish is performed on an automatic polisher using a polishing cloth with a soft nap texture and 6-micrometer diamond paste. The final polish is achieved using deep nap or pile cloth similar to billiard cloth with a suspension of 0.1 micrometer or finer aluminum oxide in water.

   Titanium and refractory alloys require an etch-polish cycle (using a slurry of hydrogen peroxide, water, and 0.1 micrometer or finer aluminum oxide) which is accomplished between a diamond polish and a final polish procedure. The final polish for titanium and refractory alloys is accomplished on a vibratory polisher using a deep pile cloth with a suspension of 0.1 micrometer or finer aluminum oxide in water.
10. Samples are etched by swabbing. Examples of some typical etchants used are given below:

Material	Etchant
Steels	2% HNO_3 and 98% Denatured Anhydrous Alcohol
Nickel Base Alloys	100 ml HCl, 5 g $CuCl_2 \cdot 2H_2O$, and 100 ml Denatured Anhydrous Alcohol
Titanium Alloys	2% HF and 98% H_2O or 2% HF, 3% HNO_3, and 95% H_2O

SOURCE: L. R. Gatto and T. D. DiLullo.[24]

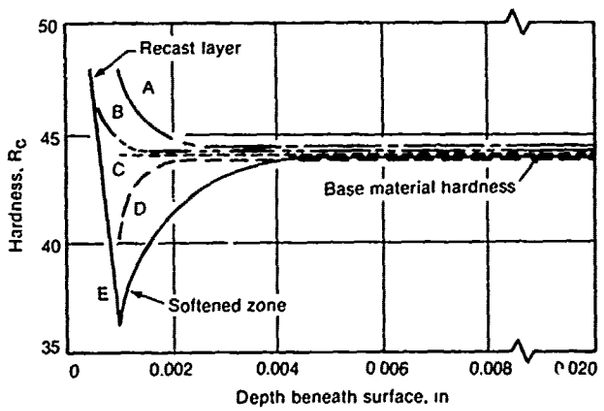


Figure 18.3-15 Microhardness traverses on Inconel Alloy 718 (solution treated and aged) from a variety of machining processes. Key: A, roughing EDM and shot peening; B, gentle ECM and glass bead peen; C, gentle grinding; D, ECM; E, EDM. (G. Bellows and D. N. Tishler[14])

When determining the microhardness using a Knoop indenter, a 100-gram load is generally employed. With this load and carefully performed readings, accurate hardness readings can be made to within 0.001 inch [0.025 mm] of the surface without producing edge yielding. Surface hardness readings to within 0.0005 inch [0.0127 mm] of the surface may be made using 25- to 50-gram loads, but extreme care must be taken even with these light loads. It is recommended that if the light load is used, hardness readings also be taken at a considerable distance from the edge and compared with 100- and 500-gram load Knoop readings. Knoop readings are generally converted to Rockwell C readings for a ready appreciation of the hardness relationships which exist near and below the affected surface layer.

Residual Stress Determination

Distortion may occur in the manufacture of components as a result of heat treating or material removal processes which can leave substantial residual stresses in the surface layers. There are several ways of determining the residual stress profile. The two most common are X-ray diffraction and layer removal-deflection techniques. Most of the machining-induced residual stress occurs in the first 0.0005 to 0.010 inch [0.0127 to 0.254 mm] below the surface. Some of the descriptors used in residual stress discussions are shown in figure 18.3-16. Figures 18.3-17 and 18.3-18 illustrate results of residual stress profiles determined from two materials and are typical of the range of effects observed. It should be noted that single surface residual stress measurements can be quite misleading, and a profile for the first few thousandths of an inch below the surface is essential. The peak value and its depth below the surface are related to the high cycle fatigue strength and magnitude of distortion. For example, note in figure 18.3-18 that the surface residual stress is zero, yet substantial stress is present less than 0.001 inch [0.025 mm] below the surface.

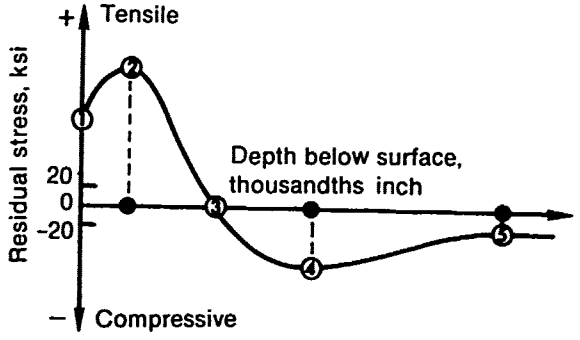


Figure 18.3-16 Residual stress profile descriptors. Key: 1, surface residual stress—value at zero depth; 2, peak stress (tensile)—value at defined depth; 3, cross over—depth in thousandths inch; 4, peak stress (compressive)—value at defined depth; 5, depth of residual stress—depth below the surface where stress declines to and remains less than 20,000 psi or an inconsequential value or less than 10% of tensile strength. (G. Bellows[13])

Carefully measured distortion on strip test specimens as shown in figures 18.3-19 and 18.3-20 can also be used as an overall residual stress indicator. In these measurements the initially flat and unstressed blank, figure 18.3-19, has one surface machined by the process being investigated. The distortion after the test cut is measured in the fixture shown in figure 18.3-20. The distortion variation with different process intensities is illustrated in the grinding of D6ac as shown in figure 18.3-21.

The use of X-ray diffraction for measuring residual stress has by and large superseded the deflection test strip method. Much smaller areas can be measured with greater accuracy. Accuracy of plus or minus 5 percent can be obtained.

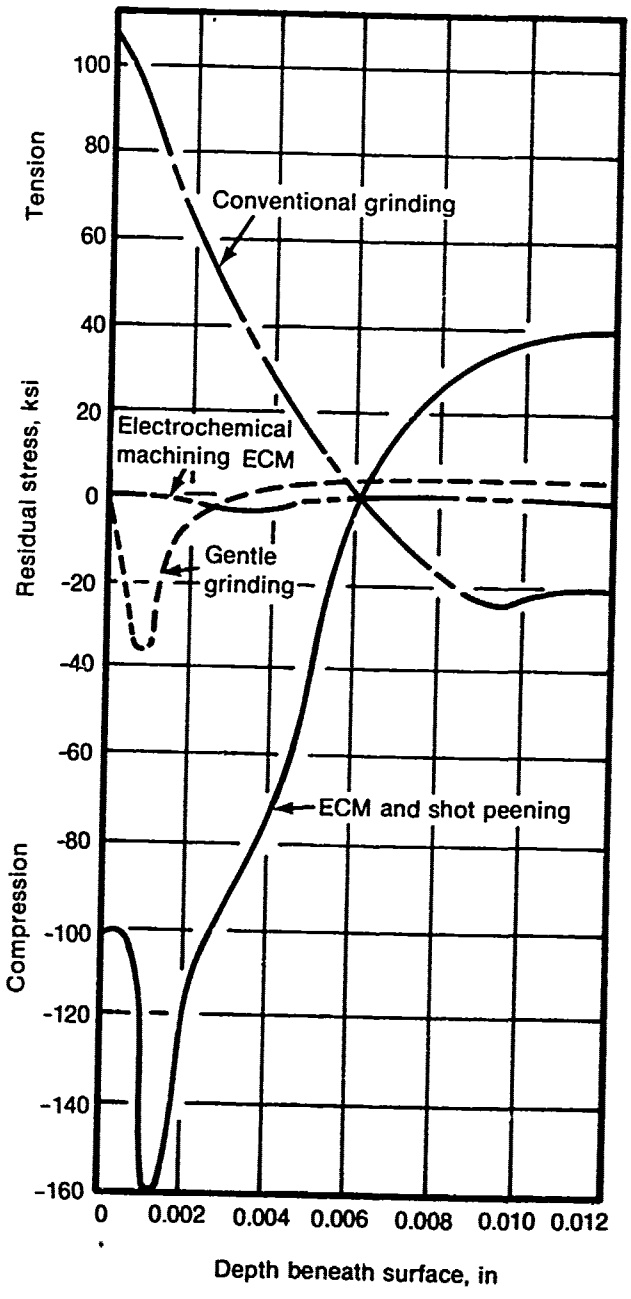


Figure 18.3-17 Residual stress produced in Inconel Alloy 718 (solution treated and aged) by several machining processes. (G. Bellows and D. N. Tishler[14])

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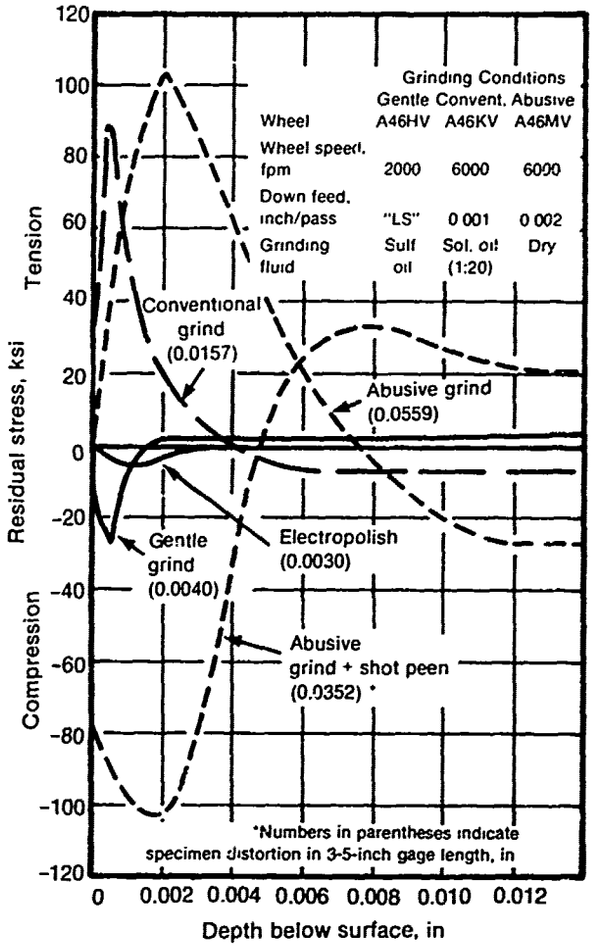


Figure 18.3–18 Residual surface stress in 4340 steel (quenched and tempered, 50 R_C) produced by surface grinding. (M. Field, J. F Kahles, and J. T. Cammett[12])

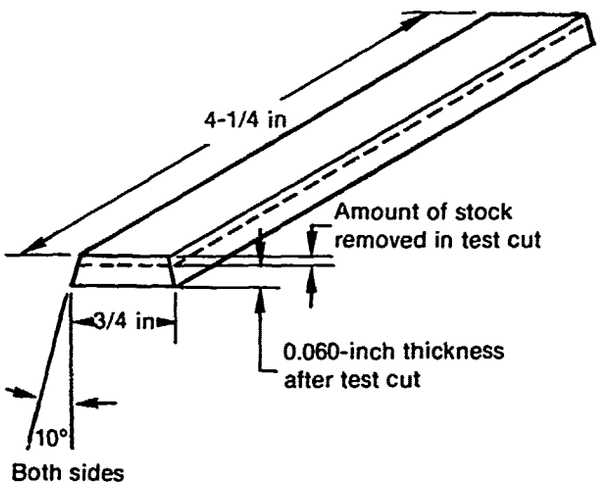


Figure 18.3–19 Distortion and residual stress test specimen. (M. Field, J. F. Kahles and J. T. Cammett[12])

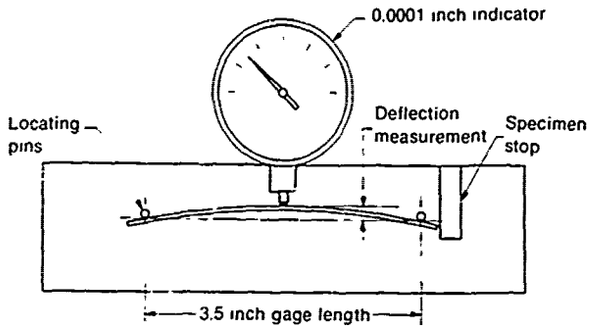


Figure 18.3–20 Deflection measurement fixture. (M. Field, J. F. Kahles and J. T. Cammett[12])

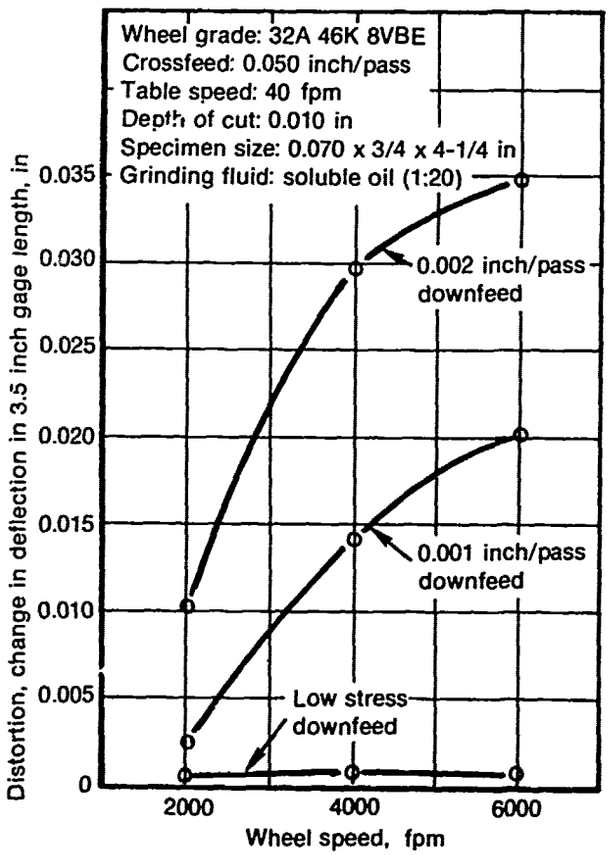


Figure 18.3–21 Change in deflection versus wheel speed for surface grinding D6ac steel (quenched and tempered, 56 R_C). Effect of down feed. (M. Field, W. P. Koster and J. B. Kohls[15])

Fatigue Strength Testing

It is well established that variations in material removal operations can produce great differences in the mechanical performance of the workpiece material. Fatigue strength is perhaps the most sensitive property. The extensive range of process influence on high cycle fatigue strength is shown in table 18.3-7 for Ti-5Al-2.5Sn alloy and in table 18.3-8 for Inconel Alloy 718. High cycle and low cycle fatigue strengths are dynamic properties that are surface dependent and are linked on a simple continuum for AF 95 (Rene 95) in figure 18.3-22. Similar effects are found at elevated temperatures. For the simple screening tests that are part of the standard data set, however, it is sufficient to collate or compare results from room temperature, full-reverse cantilever bending high cycle fatigue tests, the setup for which is shown in figure 18.3-23. A test specimen that produces repeatable results and exposes an ample test surface to the test stress level is shown in figure 18.3-24. The results are frequently displayed on an S-N (stress versus number of cycles to failure) curve, figure 18.3-25, or in a bar graph using the stress level at 10^7 cycles as representative of the endurance strength.

TABLE 18.3-7 Comparative High Cycle Fatigue Strengths and Surface Roughnesses of Ti-5Al-2.5Sn Alloy (formerly A110 Alloy) from Several Processes

PROCESS	FATIGUE STRENGTH*		SURFACE ROUGHNESS	
	ksi	MPa	μin R_a	μm R_a
Ultrasonic machining (USM)	98	676	20	0.5
Conventional slab milling (CML)	86	593	6 to 8	0.15 to 0.20
Chemical machining plus vacuum anneal (CHM)	77	531	30 to 40	0.8 to 1.0
Shot peened (CPE)†	76	524	—	—
As rolled	61	421	—	—
Chemical machining (CHM)	59	407	30 to 40	0.8 to 1.0
Conventional traverse grinding (CGS)	53	365	16 to 18	0.40 to 0.45
Conventional longitudinal grinding (CGS)	52	359	16 to 18	0.40 to 0.45
Electrical discharge machining (EDM)	22	152	30 to 40	0.8 to 1.0

SOURCE: Data from R. J. Rooney.[27]

*Room temperature, 10^7 cycles full-reverse bending.

† P28 steel shot; 0.010 to 0.012 A_2 Almen level.

TABLE 18.3-8 Effect of Machining and Peening on Fatigue Strength of Inconel 718 (Solution Treated and Aged 44 R_c)

OPERATION	FATIGUE STRENGTH*		
	ksi	MPa	Percent of gentle grind
Gentle surface grinding	60	414	100
Conventional surface grinding	24	165	40
Gentle turning	60	414	100
Abusive turning	60	414	100
Standard ECM	39	269	65
Off-standard ECM	39	269	65
Standard ECM plus Peen	78	538	130
Off-standard ECM plus Peen	67	462	112
Finish EDM	22	152	37
Rough EDM	22	152	37
Finish EDM plus Peen	66	455	110
Rough EDM plus Peen	75	517	125
Electropolishing (ELP)	42	290	70
ELP plus Peen	78	538	130

*Room temperature, 10^7 cycles full-reverse bending.

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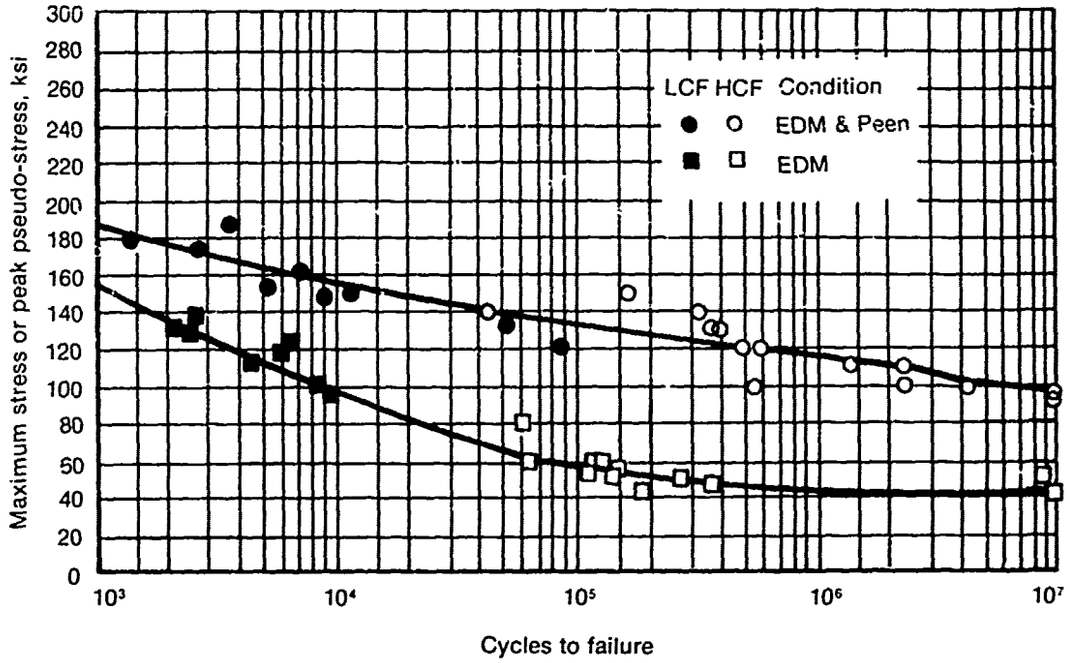


Figure 18.3–22 Example of high cycle and low cycle fatigue strength continuum in test data from electrical discharge machining of AF 95 (Rene 95) at 1000°F. (G. Bellows and W. P. Koster[16])

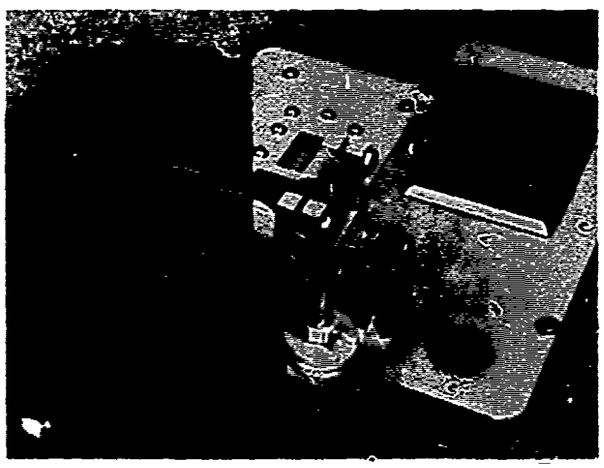


Figure 18.3–23 High cycle fatigue test setup. (M. Field, J. F. Kahles and J. T. Cammett[12])

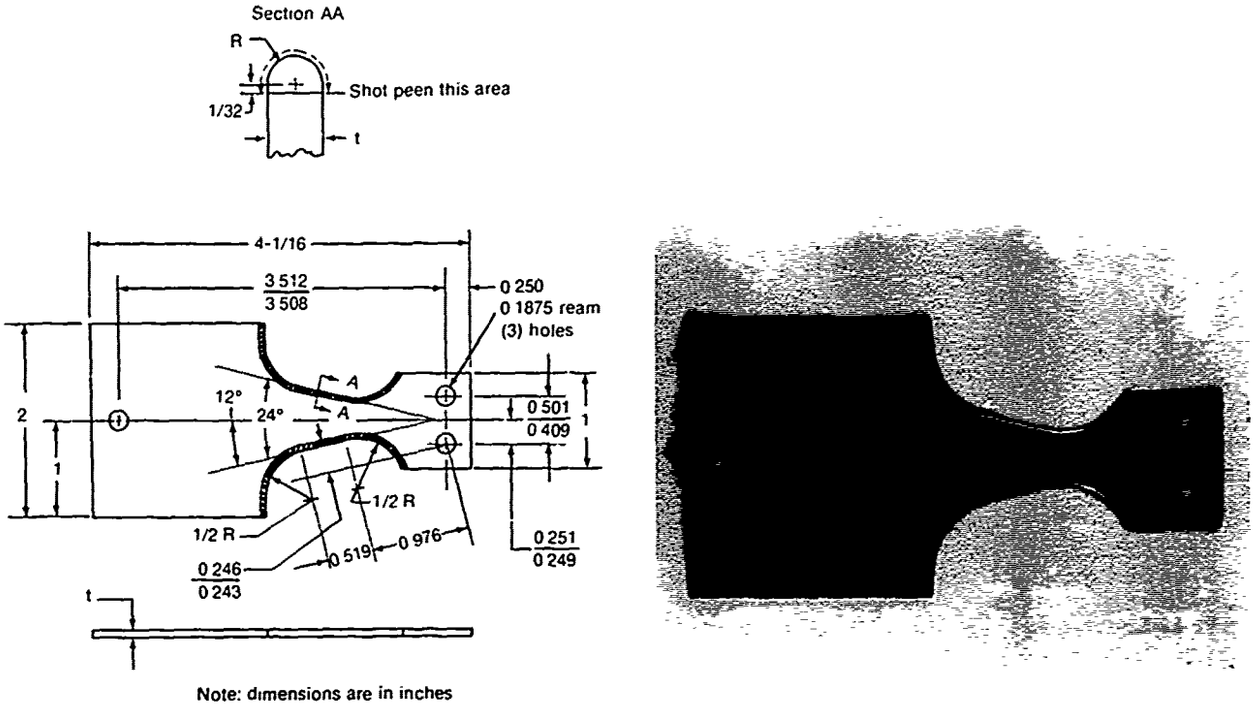


Figure 18.3–24 Fatigue test specimen with tapered test section to secure a test area subjected to test stress. (M. Field, J. F. Kahles and J. T. Cammett[12])

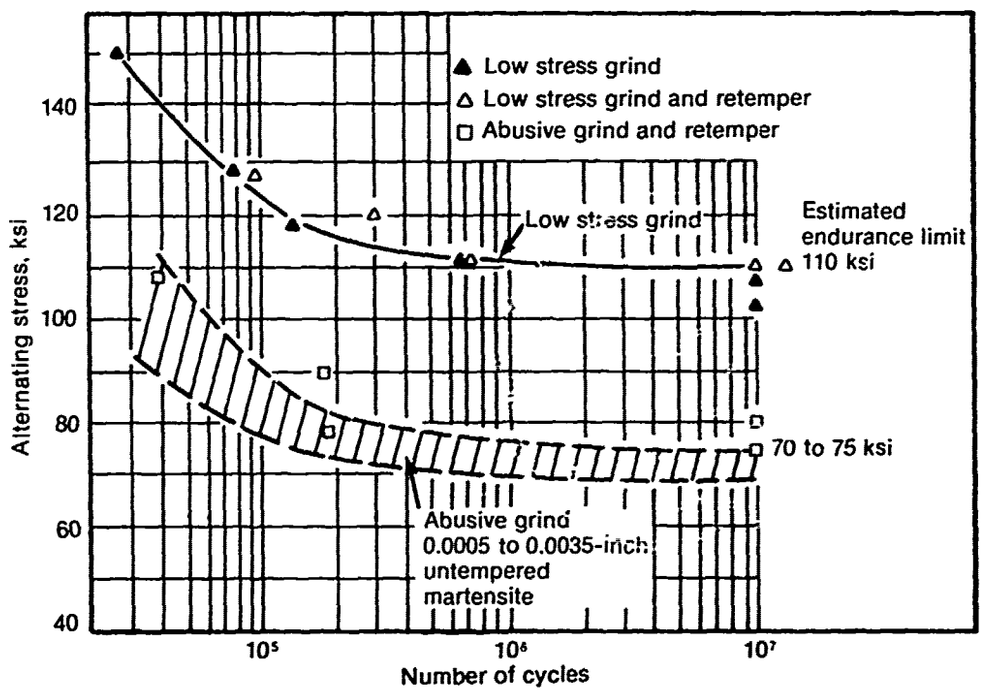


Figure 18.3–25 S-N curve of high cycle fatigue test data of ground 4340 steel (quenched and tempered, 50 R_C). (M. Field, J. F. Kahles and J. T. Cammett[12])

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Surface Roughness and Fatigue Strength

In the testing of several alloys. it has been observed that surface roughness is not the critical factor that it has traditionally been assumed to be. It appears that the effects of roughness can be overshadowed by the effects of residual stresses. the presence of metallurgically changed phases. plastically deformed surfaces or other effects. As indicated in figure 18.3-26. the gently ground surfaces on 4340 steel produced the best high cycle fatigue strengths. Notice. however. that in the case of abusively ground surfaces other factors were at work within the range of surface roughnesses tried. and all roughnesses developed the same 65 ksi [448 MPa] fatigue strength. Observe also that in the milling of Ti-6Al-6V-2Sn and in the face turning of Inconel Alloy 718. the fatigue strength did not vary with surface roughness.

Further studies of the effects of surface roughness on fatigue strength have been made in which the data represent conditions where residual stresses from the machining process were essentially zero. Figure 18.3-27 shows the differences among three materials that range from practically no effect from surface roughness (Inconel Alloy 718) to a substantial effect (the two titanium alloys). For alloys where surface roughness has little or no effect on fatigue strength. a considerable potential for cost reduction exists.

In analyzing surface roughness. it is not implied that the effect of scratches. tool marks. sharp corners and other geometric considerations can be overlooked. The effect of these factors as producers of stress concentrations leading to premature fatigue failure is well established.

In summary. an important point to consider is to test and evaluate the influence of finish and other factors affecting the endurance strength of particular material and process combinations. Caution must be exercised before drawing general conclusions from the limited data available at this time concerning surface roughness and surface integrity interrelationships.

Stress Corrosion Cracking

The two surface integrity effects having the most direct bearing on design and application considerations are fatigue strength and stress corrosion cracking propensity. The former lends itself to a fairly simple comparison. as has already been noted. The latter is more complex and no simple evaluation procedure has evolved that yields comparable data. The number of possible combinations of materials. processes. metallurgical states. energy levels. service stresses. environmental fluids or gases is beyond counting. Therefore. each application should be analyzed for its own situation and evaluated by carefully structured testing.

Combined Effects

It is rare that the dynamic properties results can be attributed to a single surface integrity effect. such as residual stress. finish. hardness. etc. One of the more pronounced relationships which has been observed exists between the peak residual stress value and the fatigue endurance strength. as demonstrated in figure 18.3-28. The tri-axis graph. figure 18.3-29. illustrates the relationships among fatigue endurance strength. residual stress and surface roughness for Inconel Alloy 718. These results are for specific materials and process combinations. and other combinations may demonstrate different relationships. Caution should be taken not to draw general conclusions from the limited data available.

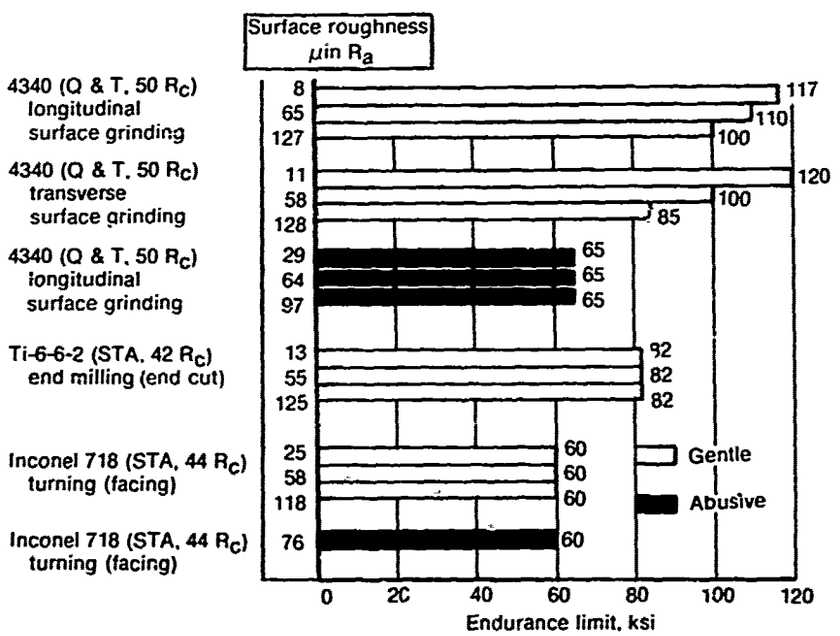


Figure 18.3-26 Summary of high cycle fatigue strengths—surface roughness study. Fatigue strength in full-reverse bending at 10^7 cycles at room temperature. (W. P.Koster et al[9])

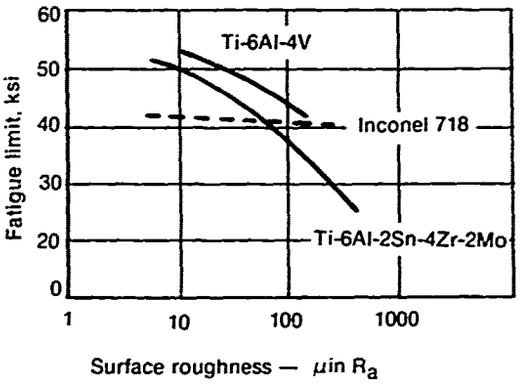


Figure 18.3–27 Fatigue strength versus surface roughness with negligible residual surface stress (full-reverse bending at 10^7 cycles at room temperature). (G. Bellows and W. P. Koster[16])

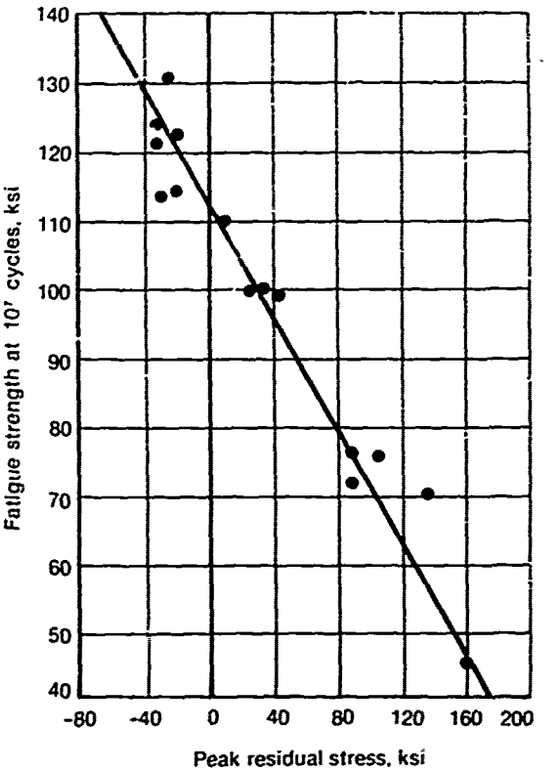


Figure 18.3–28 Correlation between peak residual stress and fatigue strength in 4340 steel at various levels of grinding intensity. Flat tapered specimens were tested in full-reverse bending. (W. P. Koster[11])

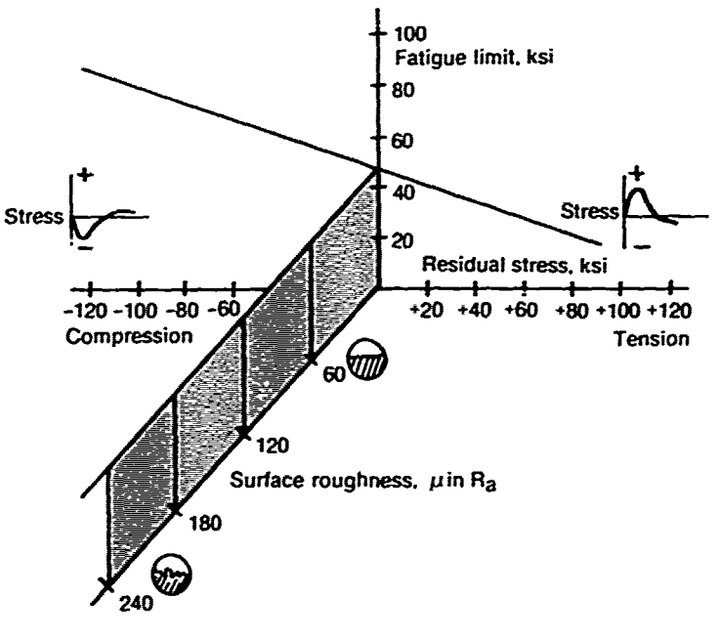


Figure 18.3–29 Relationships among surface roughness, residual stress and high cycle fatigue endurance strength at room temperature in Inconel Alloy 718 (solution treated and aged, 44 R_C). (G. Bellows and W. P. Koster[16])

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GENERAL GUIDELINES

There is an increasing awareness that surface integrity effects can significantly impact product integrity, longevity and reliability. Specific data on every material and process combination are not available. Reliable data must also consider the several processing intensities that may be used and the several metallurgical states that may be presented for processing. Until more data can be accumulated, reliance must be placed on sets of guidelines. Detailed data supporting the guidelines are contained in the references. Basically, each level of processing intensity for each manufacturing process has a distinct set of surface integrity effects when it is applied to a specific metallurgical state of a workpiece material.

Precautions in Use of Guidelines

The following guidelines can only serve as general or starting recommendations. Data and experience gathered to date indicate that these practices lead to the production of unimpaired or enhanced surfaces. However, knowledge of the surface technology at this time is such that general recommendations are not always applicable to all specific surface integrity situations. For highly critical or highly stressed surfaces, it is mandatory to make specific individual evaluations.

Surface integrity control generally results in increased costs and decreased production rates. Therefore, surface integrity practices should be implemented only where a definite need exists. Process parameters which enhance surface integrity should be applied selectively to critical parts or critical areas of given parts to help minimize costs.

The guidelines are intended primarily for processes used in producing the final or finished surface of a workpiece. It is important to know the depth of surface alterations produced during the roughing or prior operations so that adequate provision can be made for removing any damaged layers. In maintaining surface integrity, the sequence of operations is as important as the specific processing level.

Ample recognition must be given to the necessity for relentless process control once the desired surface integrity processing parameters have been selected. Equal consideration for control of the metallurgical state and condition of the material being presented for processing is essential.

Key Indicators of Need for Surface Integrity Control

- Hazards to life and/or the possibility of high economic property loss.
- Distortion in thin parts.
- Cracking in processing or in service.
- Short service life.
- Requirements for manufacturing parts using sensitive alloys, such as high strength steels, nickel and cobalt base high temperature alloys, titanium alloys, beryllium, and refractory alloys.
- New or indeterminate environmental conditions including stress, temperature, and atmosphere.
- Requirements for designs which approach more complete utilization of material properties.
- Manufacturing requirements calling for use of material removal processes, such as rough conventional machining, heavy grinding, EDM and laser beam machining, which characteristically cause surface alternations.

Guidelines for Material Removal Processes in General

While most of the surface integrity investigations to date have involved material removal processes, this does not mean that forming, joining, coating or other processes are exempt from surface integrity considerations. It only indicates that insufficient data are available for these processes.

Some general guidelines for all material removal processes are as follows:

1. Thorough component or product testing is one of the best assurances for and checks of surface integrity. The tests should be run with surfaces produced by the complete and exact sequence of production operations.
2. Apply surface integrity requirements only to the critical or highly stressed zones of the component part. Do not apply "all over".
3. Highly stressed areas of critical components should be evaluated carefully to assess the impact of the full sequence of processes that generate the "as-shipped" surface. The control of the sequence of processes is as important to surface integrity as is the selection and maintenance of the process operating parameters.
4. Control of the material metallurgical state is as important as control of the process parameters.
5. Material inhomogeneities or anomalies (sometimes even those within specification limits) can have component integrity effects as serious as the surface integrity effects from different process intensities.
6. Designers, shop supervisors, and quality control and process engineers must be educated and trained in order to increase their appreciation of the magnitude of surface integrity effects from manufacturing processes.
7. The surface integrity from processes other than material removal or machining processes should also be evaluated.
8. The surface integrity effects from conventional machining are of the same magnitude as those from nontraditional machining.
9. Metallographic sections at high magnification, taken parallel and perpendicular to the lay pattern, provide an effective early alert to potential surface integrity problems.

10. Post-processing treatments, such as heat treatment, shot peening, roller burnishing, low stress grinding, etc., may offset some, but not necessarily all, of the otherwise detrimental surface integrity effects.

11. Hand-controlled operations have a tendency to produce variability in surface effects and should be considered suspect.

12. Low process energy intensities and low material removal rates are characteristic of most, but not all, material removal processes which provide acceptable surface integrity.

13. Rigid, high quality machine tools and fixtures are desirable.

14. Cutting fluids should be fresh or well controlled and carefully, completely and quickly removed from the workpiece when the operation is completed.

15. Deburring of all machined edges is desirable.

16. Parts stored for extended periods should be covered with a protective coating to prevent corrosion.

Comparison of Altered Material Zones from Material Removal Processes

Examination of several thousand section photomicrographs of surfaces generated by a wide variety of material removal processes has provided data for table 18.3-9, a summary of the depth of surface integrity effects. These data show the maximum depth of alterations observed to date for two particular operating levels of each listed process. The two process intensity levels displayed represent (a) finishing, "gentle" or low stress conditions or (b) roughing, "off-standard" or "abusive" conditions. The former represent what might be expected from well controlled, good surface integrity operations, while the latter represents high intensity or even accidental conditions, such as a delayed application of coolants. The data cover the full range of material types.

Implementing Surface Integrity Programs

The following steps are recommended for instituting an in-house surface integrity program:

Education and Training

Manufacturing and product engineering personnel are generally not sufficiently acquainted with the many types of surface alterations which can be produced during material removal operations. Product or design engineers generally do not realize that high temperatures prevail in conventional machining at the workpiece-tool interface, while manufacturing people often do not realize the extent to which metallurgical changes occur and how seriously they lower mechanical properties. This situation points out the advisability of educational efforts to help increase general cognizance of the importance of surface integrity control. In addition to general educational programs, specific training is required for machine operators and quality control personnel. Some companies, for example, require qualification of personnel in order to perform drilling and reaming of holes. Other plants give short courses on how to inspect for rehardened and overtempered martensite in the manufacture of high strength steel components.

Specifying Surface Integrity Quality

Overspecification or too extensive use of surface integrity quality specifications can significantly increase manufacturing costs. Component part drawings should call for the surface integrity controls only on the areas or zones that are highly stressed or critical in preference to notes calling out "apply all over". Good value engineering and coordination with manufacturing personnel will produce design details with the best component integrity.

Manufacturing Engineering

Carefully integrated machine, operation and inspection planning will improve the surface integrity results and contain the manufacturing costs. Simple metallographic examination of test pieces can provide a preview of the surface integrity results to be expected during production. These checks can prevent expensive and time consuming surprises during initial production.

Maintaining Operating Parameters

Particular attention should be given to the necessity for maintaining specified operating parameters. Machine operators should be thoroughly trained to follow the proper procedures outlined by manufacturing engineering. All parameters for material removal should be specified by manufacturing engineering. For chip removal operations, these include tool material, tool geometry, cutting speed, feed, cutting fluid, and tool life (maximum number of parts per tool grind). Similarly, appropriate parameters must be set up for operations such as grinding, EDM and ECM. Machinists should be informed as to the reason and necessity for maintaining good surface integrity and surface quality and should be made aware that it is not currently possible to guarantee maintenance of surface integrity by final part inspection. Management needs to be ever alert to the desire on the part of operators to try "just one more notch" on the control. Without requalification, this relaxation of standards may result in loss of surface integrity.

Quality Audits

Since no instrument can measure the surface integrity produced, reliance is frequently placed on process control. Good quality control practice includes randomly spaced, periodic audits of the operating conditions actually being used as compared to the preplanned values. Some companies use the manufacturing engineer most knowledgeable in a process to conduct the audit.

Guidelines and Specifications

The guideline concept has been used by some organizations to assist in the implementation of surface integrity processing. Booklets can be designed to fit the specific needs of a company, division, or department. Guidelines are particularly useful prior to the development of practical and meaningful specifications.

Preparation of processing specifications is highly recommended for critical parts. In fact, some of the aerospace producers have written detailed manufacturing specifications incorporating machining parameters and procedures in an effort to maintain surface integrity. These specifica-

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TABLE 18.3-9 Comparison of Depth of Surface Integrity Effects Observed in Material Removal Processes

PROPERTY AND TYPE OF EFFECT	CONDITION	MAXIMUM OBSERVED DEPTH OF EFFECT* inch / millimeter							
		Turning or Milling	Drilling	Grinding	Chemical Machining	Electro-chemical Machining	Electro-chemical Grinding	Electrical Discharge Machining	Laser Beam Machining
MECHANICAL ALTERED MATERIAL ZONES									
Plastic deformation (PD)	finishing‡	0.0017	0.0008	0.0003	***	***	***	***	***
	roughing #	0.0030	0.0047	0.0035	***	***	***	***	***
	finishing	0.043	0.020	0.008	***	***	***	***	***
	roughing	0.076	0.119	0.089	***	***	***	***	***
Plastically deformed debris (PD^2)	finishing	***	***	0.0005	***	***	***	***	***
	roughing	***	***	0.0013	***	***	***	***	***
	finishing	***	***	0.013	***	***	***	***	***
	roughing	***	***	0.033	***	***	***	***	***
Hardness alteration†	finishing	0.0005	0.0010	0.0015	0.0010	0.0014	0.0007	0.0010	—
	roughing	0.0050	0.0200	0.0100	0.0031	0.0020	0.0015	0.0080	—
	finishing	0.013	0.025	0.038	0.025	0.036	0.018	0.025	—
	roughing	0.127	0.508	0.254	0.079	0.051	0.038	0.203	—
Microcracks or Macrocracks	finishing	0.0005	0.0005	0.0005	***	0.0003	0.0000	0.0005	0.0006
	roughing	0.0015	0.0015	0.0090	***	0.0015	0.0010	0.0070	0.0040
	finishing	0.013	0.013	0.013	***	0.008	0.000	0.013	0.015
	roughing	0.038	0.038	0.229	***	0.038	0.025	0.178	0.102
Residual stress‡	finishing	0.0060	—	0.0005	0.0010	0.0000	0.0000	0.0020	0.0002
	roughing	0.0140	—	0.0125	0.0010	0.0000	0.0000	0.0030	—
	finishing	0.152	—	0.013	0.025	0.000	0.000	0.051	0.005
	roughing	0.356	—	0.318	0.025	0.000	0.000	0.076	—
METALLURGICAL ALTERED MATERIAL ZONES									
Recrystallization	finishing	—	—	0.005	***	***	***	***	***
	roughing	—	—	—	***	***	***	***	***
	finishing	—	—	0.013	***	***	***	***	***
	roughing	—	—	—	***	***	***	***	***
Intergranular attack (IGA)	finishing	***	***	***	0.0003	0.0003	0.000	***	***
	roughing	***	***	***	0.0060	0.0015	—	***	***
	finishing	***	***	***	0.008	0.008	0.000	***	***
	roughing	***	***	***	0.152	0.038	—	***	***
Selective etch, pits, protuberances	finishing	0.0004	—	0.0002	0.0006	0.0004	0.0001	0.0005	—
	roughing	0.0010	0.3000	0.0004	0.0015	0.0025	0.0005	0.0016	—
	finishing	0.010	—	0.005	0.015	0.010	0.003	0.013	—
	roughing	0.025	0.076	0.010	0.038	0.064	0.013	0.041	—
Metallurgical transformations	finishing	0.0004	0.0015	0.0005	—	0.0000	0.0001	0.0006	0.0006
	roughing	0.0030	0.0200	0.0060	—	0.0002	0.0003	0.0050	0.0015
	finishing	0.010	0.038	0.013	—	0.000	0.003	0.015	0.015
	roughing	0.076	0.508	0.152	—	0.005	0.008	0.127	0.038
Heat-affected zone (HAZ) or Recast layers	finishing	0.0001	—	0.0007	***	***	***	0.0006	0.0006
	roughing	0.0010	0.0030	0.0125	***	***	***	0.0050	0.0015
	finishing	0.003	—	0.018	***	***	***	0.015	0.015
	roughing	0.025	0.076	0.318	***	***	***	0.127	0.038

SOURCE: G. Bellows and W. P. Koster.[16]

NOTE: A dash (—) in the table indicates no or insufficient data.
A triple asterisk (***) in the table indicates no occurrences or not expected.

*Normal to the surface.

†Depth to point where hardness becomes less than ±2 points R_c (or equivalent) of bulk material hardness (hardness converted from Knoop microhardness measurements).

‡Depth to point where residual stress becomes and remains less than 20 ksi [138 MPa] or 10% of tensile strength, whichever is greater.

‡Finishing, "gentle" or low stress conditions.

Roughing, "off-standard" or abusive conditions

tions, even though widely used in subcontract work, are generally considered proprietary and under the control of the prime contractor. It is suggested that the manufacturing or engineering departments of the large producers be contacted directly concerning the availability of their specifications.

Testing Specific Applications

Thorough component or product testing is one of the best assurances for checking of surface integrity. Tests should be conducted on surfaces of parts that have completed the full sequence of processing steps. While metallographic examination and some nondestructive tests can be helpful and can reveal clues to the surface integrity, the most critical applications should preferably be supported by specific specialized testing where the test conditions reflect the expected operating environment.

SPECIFIC GUIDELINES

While several thousand bits of data have been used to develop specific surface integrity guidelines, only the summary tabulations or statements are included in this handbook.[1] These summaries are accompanied by a representative selection of specific data to illustrate the types of effects observed.

The guidelines are organized and presented according to the process groups that follow:

- Mechanical Processes, including milling, turning and drilling
- Abrasive Processes, including grinding, sanding and low stress grinding
- Electrical Processes, including electrochemical machining and electrochemical grinding
- Thermal Processes, including electrical discharge machining, laser beam machining and electron beam machining
- Chemical Processes, including chemical machining and photochemical machining

For each process group, the following information is provided:

- Depth of surface integrity effects observed
- Photomicrographs of good and poor surfaces
- Representative residual stress data
- High cycle fatigue strength values for several materials
- Minimum or standard data sets where available
- Comments by major material groups
- Comments on special situations
- List of guidelines

These data emphasize the importance of the machining process; however, equal consideration should be given to the metallurgical state of the workpiece material.[2]

Specific Guidelines and Data for MECHANICAL Material Removal Processes

Conventional mechanical machining surface integrity guidelines have been developed principally from data generated by single- or multiple-point tools operated in the turning, milling (end, peripheral or face) or drilling mode. Table 18.3-10 combines and summarizes the surface integrity data observed from all of these. Figures 18.3-30 through 18.3-44 illustrate both good and poor surface conditions as seen in cross section, high magnification photomicrographs. Figures 18.3-45 and 18.3-46 show residual stress profiles found from the surface inward a few thousandths of an inch perpendicular to the surface. Figures 18.3-47 and 18.3-48 compare the high cycle fatigue strengths of a variety of materials. These strengths are the values at 10^7 cycles of failure from full-reverse bending cantilever tests run on tapered section specimens at room temperature. The reference base or "handbook" value in most cases was data generated from low-stress-ground specimens or hand-polished specimens. Other mechanical material removal illustrations are figures 18.3-6, 18.3-7, 18.3-9 and 18.3-26.

Conventional machining processes have been used so long that it is easy to forget that they are characterized by mechanical plastic deformation, regular lay patterns and sometimes substantial heat affects from too forceful a passage of the cutter point over the surface. The degree of dullness of the tool is a major factor in determining the surface effects. With the approach of the end of the tool life, extensive roughness, tears, laps, or deposited built-up edge can result in abused surfaces. (See section 18.2, figure 18.2-19.)

Surface integrity data for the mechanical nontraditional processes are not extensive and should be investigated in critical applications using techniques suggested previously. Generally the low energy levels and gentle material removal rates result in a minimum of altered material zones.

Chip Cutting Process Guidelines that Promote Good Surface Integrity Results

1. Sharp tools are essential for establishing surface integrity in turning, milling, and similar single-point tool cutting processes. Plastic flow is frequently present and dull tools can produce laps, tears and roughness which can be initiating sites for fatigue failure.
2. Maximum flank wearlands should be limited to 0.005 to 0.008 inch [0.127 to 0.203 mm]. This is the point at which the wearland becomes visible to the naked eye.
3. Cutting parameters should be selected which provide long tool life in order to assist in keeping tools sharp.
4. Form cutters tend to produce surface damage more readily than do finishing tools which generate a form.
5. The heat from the passage of a cutting tool, especially a dull one, can produce metallurgical transformations.

6. Evidence of burning on the surface should initiate a check of the depth, which can extend to 0.010 inch [0.254 mm].

7. Residual stresses from dull cutting tools are frequently compressive, below the surface.

8. Sharp drills should be used to help avoid serious surface layer alterations.

9. Dwelling during drilling should be avoided; galling, torn or discolored surfaces should be cause for rejection or correction.

10. Drill fixturing rigidity is desirable.

11. Deburring is imperative on both the entr nce and the exit of holes.

12. Drilled and reamed holes should be chamfered on both the exit and the entrance.

13. Reaming stock allowances should be controlled.

14. A maximum number of holes per reamer should be specified and maintained despite the visual appearance of reamer.

15. Hand feeding of straight reamed holes should be avoided.

16. Alignment, tool geometry and tool condition are important controls in hand reaming.

17. Finish boring operations should maintain roughness limits and avoid laps and tears. Only very small wearlands can be tolerated with about 0.005 inch [0.127 mm] as a limit. One finish pass per cutting edge is a frequently set limit.

18. Honing is an excellent finishing operation for developing surface integrity.

19. Corrosion potential of some cutting fluids should be checked. Old fluids should be checked because old fluids often corrode workpieces more rapidly.

20. Finish roughness values should not serve as the only criteria for development of fatigue strength.

Special Comments Concerning Surface Integrity Practices for Chip Cutting Processes

Rigid, high quality machine tools are essential. They must be designed with the ranges of speeds and feeds necessary to meet surface integrity requirements. See comments below on the need for selecting speeds and feeds which give long tool life.

Cutting tools should be inspected carefully prior to use. Cutting tools must be carefully ground, and the most rigid tool design should be employed. For example, stub length drills should be used instead of a jobber's length wherever possible. Cobalt or premium grade high speed steel should be used wherever carbide is not applicable so as to do everything possible to provide a low rate of tool wear. All tools should be inspected after grinding to insure that previous wear, chipping, galling, etc., have been corrected to meet tool specifications. After grinding, the cutting edges of all tools should be protected to prevent accidental damage from transit or handling. Tools should be double checked by the machine tool operator for obvious defects.

Sharp tools help establish surface integrity in turning and milling. For chip removal operations, as for grinding operations, it is important to produce a surface which has a minimum or preferably an absence of surface alterations; that is, the surface layers should be similar to the base material below the surface.

For turning and milling, there are two very important steps which will improve surface integrity. First, select machining conditions which will give long tool life and produce good surface finish. Second, machine with sharp tools. Sharp tools minimize distortion and generally lead to better control during machining. The maximum flank wear when turning or milling should be limited to approximately 0.005 to 0.008 inch [0.127 to 0.203 mm]. A good rule of thumb is to remove the tool when the wearland becomes visible to the naked eye since the aforementioned wearland is just barely visible to the naked eye. Dull tools develop high compressive stresses which cause distortion, and very often they produce tears, laps and metallurgical alterations of the surface, including untempered and overtempered martensite in steels. For turning most alloys, carbide tools tend to have the lowest wear rate and at the same time make it possible to meet reasonable production rates. Indexable carbide tools, in particular, should be used whenever possible. This expedites the changing of cutting edges whenever tool wear reaches its specified limit.

In order to determine machining conditions which will provide long tool life, it is necessary to refer to tool life data for specific materials and material removal operations. References 3 through 6 supply data for tool materials, tool geometry, feeds, depth of cut, cutting fluids, etc., for the purpose of achieving long tool life. If tool life data are not available, the material closest in characteristics to the actual work material can be used for initial consideration of the machining parameters. In addition, it is recommended that tool life data be studied carefully in order to develop the relationship between machining parameters and tool life. In this way, one can get an idea of the effects of changes in speeds, feeds, tool materials, etc., on tool life and be in a better position to decide on departures from the recommended machining parameters.

Any evidence of burning as a result of a tool or cutter breakdown should be reported to supervision. Care must be taken to remove sufficient stock after tool breakdown to completely remove the effects of the burning which may extend as much as 0.005 to 0.010 inch [0.127 to 0.254 mm] below the machined surface.

There is a tendency for more surface damage to occur when a long cutting edge produces the final surface. This situation usually occurs when turning to a shoulder or when milling a radius into a component. The use of especially sharp cutters for finishing is desirable in order to min-

imize the alterations. For turning, whenever possible a shoulder or large radius should be generated by the finishing tool rather than being formed by the long cutting edge of a forming tool.

Sharp drills should be used to avoid serious surface alterations. Holes in highly stressed components should be free of tears, laps, and untempered or overtempered martensite. To minimize defects, the wearland on drills should be limited to 0.005 to 0.008 inch [0.127 to 0.203 mm]. Wherever possible, all hand feeding during drilling should be avoided. When drilling assemblies, a rigid machine tool or gantry type drill should be employed in preference to portable drilling equipment. Dwelling should also be avoided because it produces damage and may even friction weld the drill to the workpiece. The operator should visually check the hole and drill after each operation. If average or localized wear exceeds specifications, the drill should be replaced. If abnormal conditions develop in the hole, it should be marked and inspected thoroughly before assembly. Galling, torn surfaces, or discoloration from overheating are causes for rejection. When a drill wears excessively or actually breaks during the drilling of sensitive alloys, the operator should notify appropriate personnel so that remedial steps can be taken. Accidents of this type indicate that machining conditions have not been selected and/or used properly. Coolant-fed drills may help minimize surface damage, but no supporting data are available.

Proper drill fixturing assists in minimizing damage during drilling. When drilling holes 1/4 inch [6.4 mm] or larger, a drill fixture or bushing should be used. Where accessibility permits, a drill backup should be used to minimize burring.

Finishing of drilled holes is imperative. The entrance and exit of all holes should be carefully deburred and chamfered. All holes should be finish reamed after drilling whenever possible to insure better surface finish and surface integrity. (See comments that follow.)

Bushing clearance is needed on deep holes. For holes with depths 3 times the diameter, or more, ample clearance should be provided between the drill bushing and the workpiece for the chips to flow.

Special precautions should be taken when reaming holes in sensitive alloys. Since reaming often serves as a final hole finishing operation, all machining parameters must be controlled. Stock allowances must also be controlled. Power feeding of power driven machines should be employed for reaming of straight holes. When using power driven machines for tapered holes, hand feeding is permissible, but power feeding is preferred. Hand reaming of tapered holes using a tap wrench may be permissible after power reaming. If hand reaming is performed, special attention should be given to the selection of tool material, the reamer geometry, and the accuracy in grinding the reamer. In addition, it may be advisable to provide for alignment of the reamer to insure accuracy during the hand reaming operation.

Double ream all straight holes 5/16 inch [7.9 mm] or larger with a minimum metal removal of 3/64 inch [1.2 mm] on the diameter. On smaller holes, the minimum metal removal should be 1/64 inch [0.40 mm] on the diameter. The operator should visually check the reamer for sharpness after each operation. At the first sign of chipping, localized wear or average flank wear beyond specification, the reamer should be replaced, and the hole should be inspected. Also, regardless of the hole and reamer condition, a maximum number of holes should be specified for reamer replacement. Each reamed hole should be carefully inspected for surface roughness, galling, smearing, scratches, etc. The entrance and exit of all holes should be carefully deburred and chamfered.

Deburring and chamfering should be used to remove all sharp edges. Drilled and reamed holes should be countersunk or chamfered at the entrance and exit to remove the entire burr because sharp edges and burrs are common sources of component failure. To countersink, use power feed units if possible and use a countersink which completely avoids chattering. Generally, low spindle speeds are desirable and chamfering tools should be kept sharp. The operator should visually inspect the tool after each cut, and it should be replaced if there is any visual evidence of wear.

The breaking of edges or radiusing may be done by abrasive deburring using a low speed, power hand drill. When chamfering a part, a minimum of 0.010 inch [0.254 mm] chamfer is advisable. The break edges and chamfers should be carefully examined for compliance with surface roughness requirements. This is especially important on the entrance and exit of holes where fatigue failures have a tendency to originate. The chamfers should be carefully blended into the adjacent surfaces.

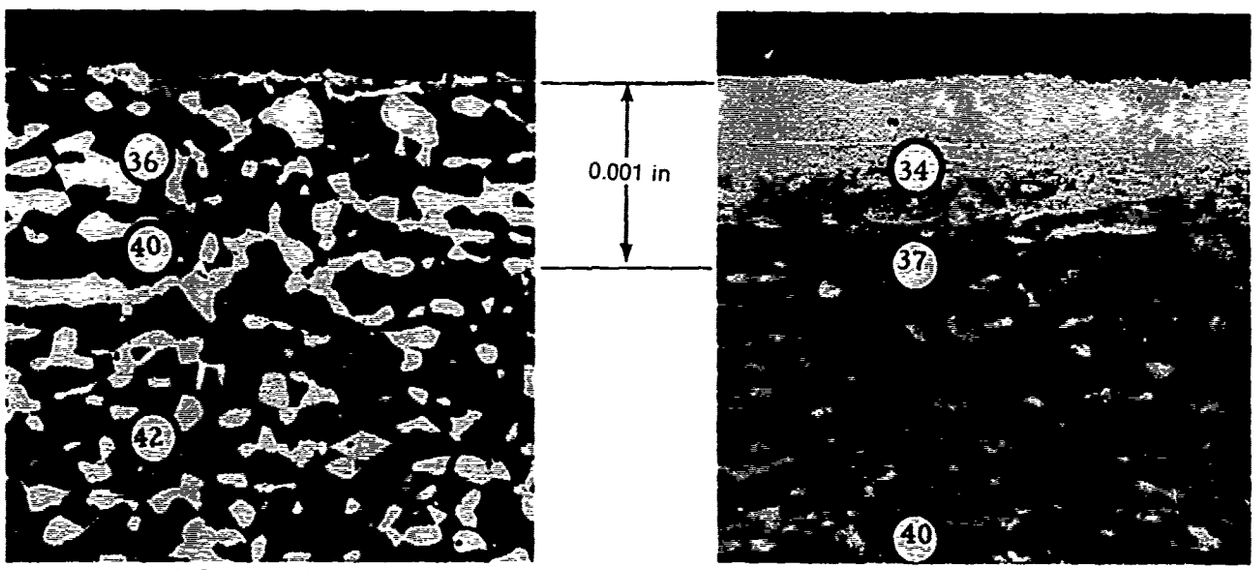
Honing is an excellent finishing operation for developing surface integrity. Honing is usually used only when finish requirements or tolerances are too close for practical use of other finishing operations such as reaming, grinding, etc. A multi-stone head is preferred; heads with steel shoes and/or steel wipers are not recommended. Honing produces less surface deformation and fewer surface integrity effects than any other conventional mechanical hole-finishing process.

Boring may be used as a finish machining operation if roughness is within the manufacturing engineering limits. When boring, extra precautions should be taken in the preparation of the cutting edge to provide extremely low surface roughness values. The tool wearland in finish boring should be limited to 0.005 inch [0.127 mm], but often it should be far less than this in order to achieve the desired accuracy and surface roughness.

18.3 Surface Integrity



Figure 18.3–30 Built-up edge from face milling 4340 steel (quenched and tempered, 50 R_C). Machining operations such as turning, drilling, milling, etc., especially under poor machining conditions, are likely to produce surfaces with a built-up edge. This photomicrograph shows that portion of the built-up edge which was left on the workpiece. Fracture analyses of failed parts have shown that cracks associated with the built-up edge have served as origins of the fracture.



GENTLE MILLING
Surface roughness:
Perpendicular to lay: 28 μin R_a
Parallel to lay: 38 μin R_a

ABUSIVE MILLING
Surface roughness:
Perpendicular to lay: 39 μin R_a
Parallel to lay: 32 μin R_a

Figure 18.3–31 Surface characteristics of Ti-6Al-6V-2Sn (solution treated and aged, 42 R_C) produced by peripheral end milling Orientation: longitudinal r urface sections perpendicular to lay. Slight evidence of distortion c n be seen on the gently mille mple. Very pronounced alterations are associated with abusive milling. A maximum hardness loss of 8 points R_C and a total affected depth of 0.004 inch can be attributed to abusive milling. Approximately 6 points R_C surface hardness loss was measured on the gently milled samples. In this case, however, the effect was much shallower, not exceeding 0.002 inch. Indicated hardness data on the photomicrographs are R_C values converted from Knoop hardness measurements. Surface roughness measurements are averages of readings made on all specimens from each group. (W. P. Koster et al[9])

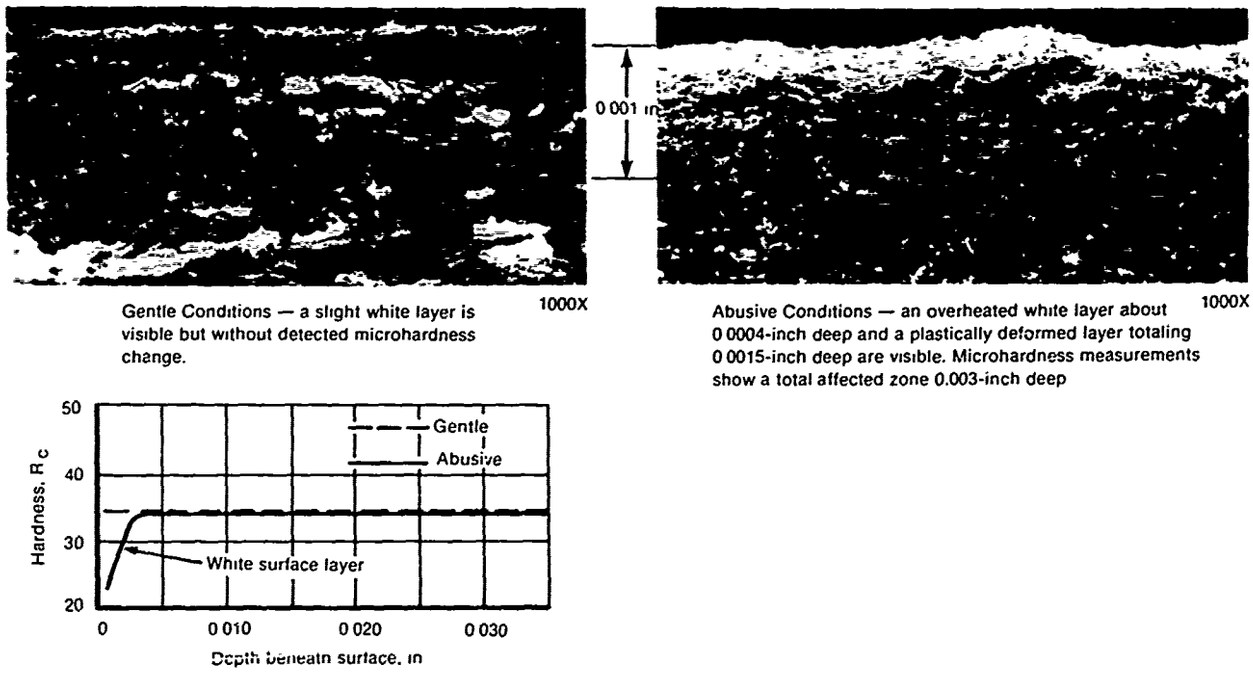


Figure 18.3–32 Surface characteristics of Ti-6Al-4V (aged, 33 R_C) produced by face milling. (Surface Integrity Encyclopedia[1])

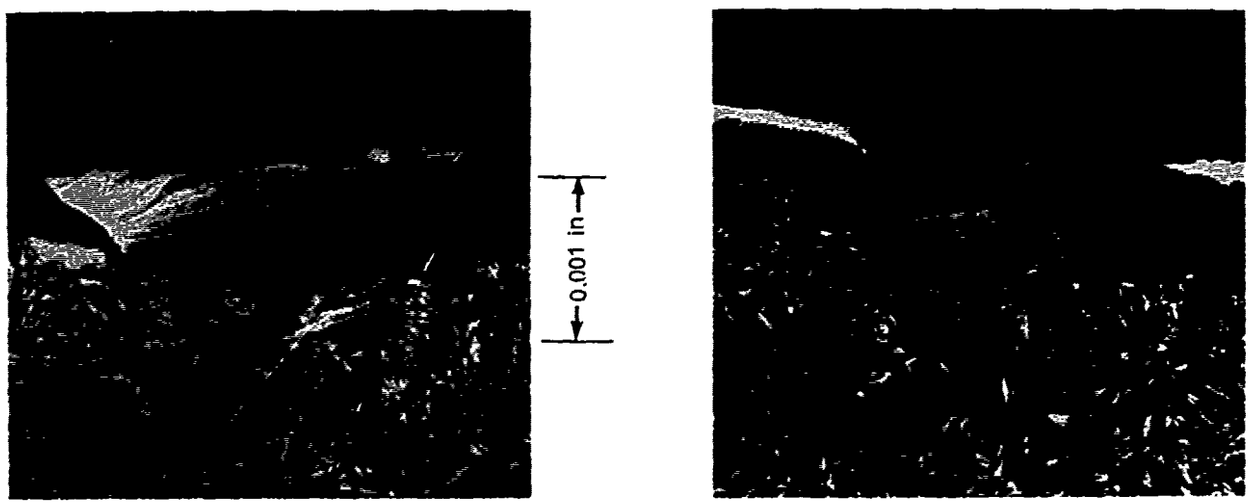
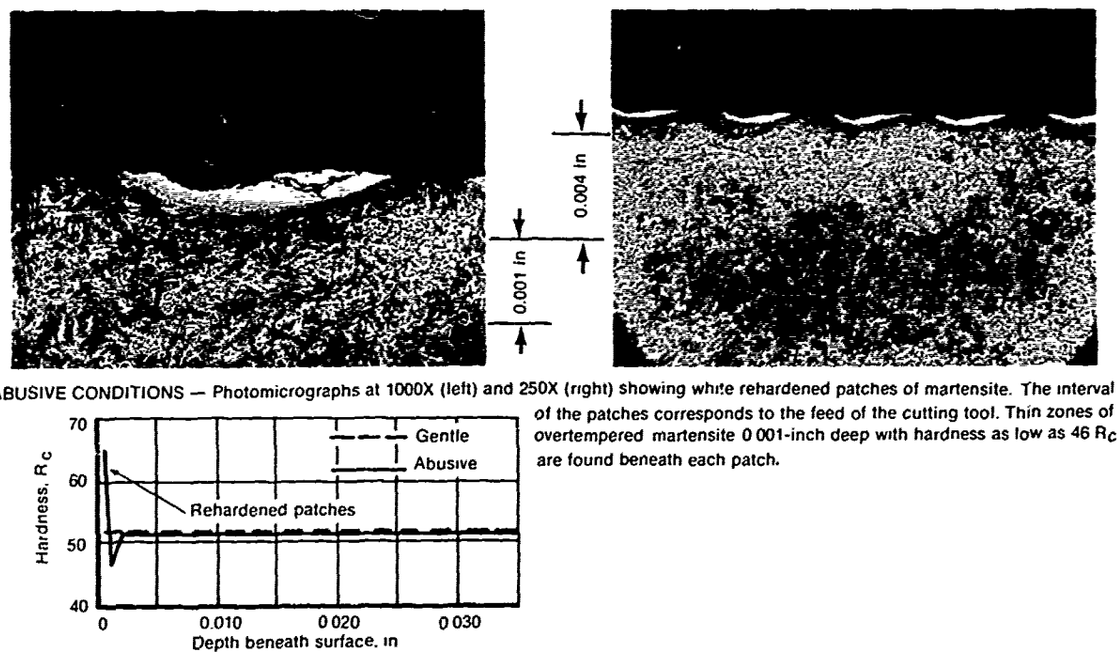


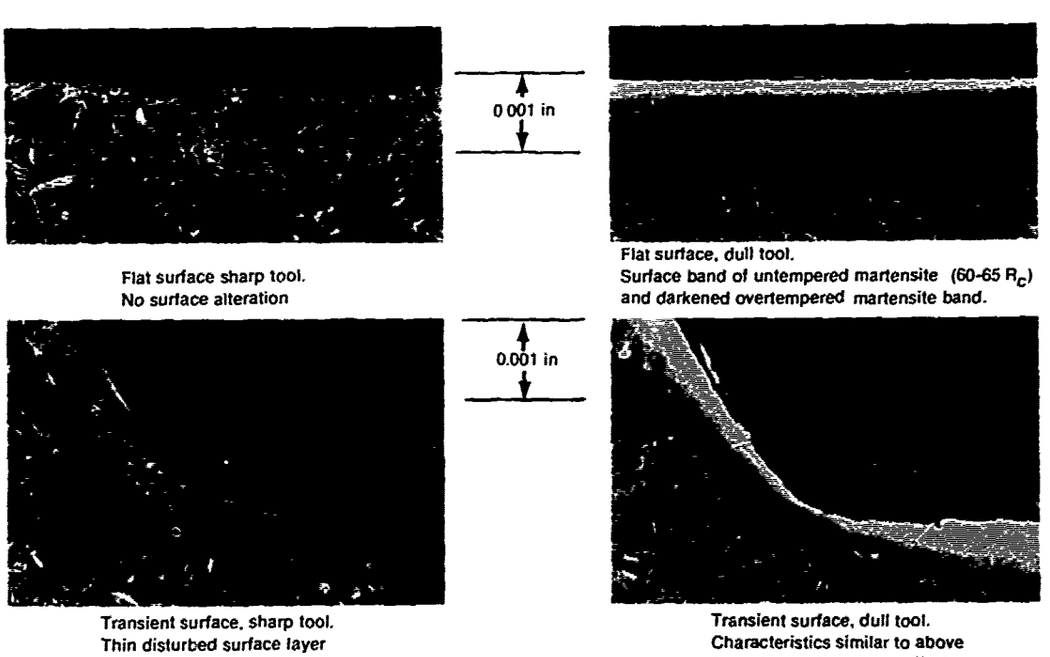
Figure 18.3–33 Surfaces produced by carbide face milling 4340 steel (quenched and tempered, 40 R_C). (M. Field, W. P. Koster and J. B. Kohls[15])

18.3 Surface Integrity



ABUSIVE CONDITIONS — Photomicrographs at 1000X (left) and 250X (right) showing white rehardened patches of martensite. The interval of the patches corresponds to the feed of the cutting tool. Thin zones of overtempered martensite 0.001-inch deep with hardness as low as 46 R_C are found beneath each patch.

Figure 18.3–34 Surface characteristics of 4340 steel (quenched and tempered, 52 R_C) produced by face milling. (M. Field, W. P. Koster and J. B. Kohls[15])



Flat surface sharp tool.
No surface alteration

Flat surface, dull tool.
Surface band of untempered martensite (60-65 R_C) and darkened overtempered martensite band.

Transient surface, sharp tool.
Thin disturbed surface layer (untempered martensite).

Transient surface, dull tool.
Characteristics similar to above but with less tempering effect.

Figure 18.3–35 Surfaces produced by carbide face milling D6ac (quenched and tempered, 48 R_C). (M. Field, W. P. Koster and J. B. Kohls[15])

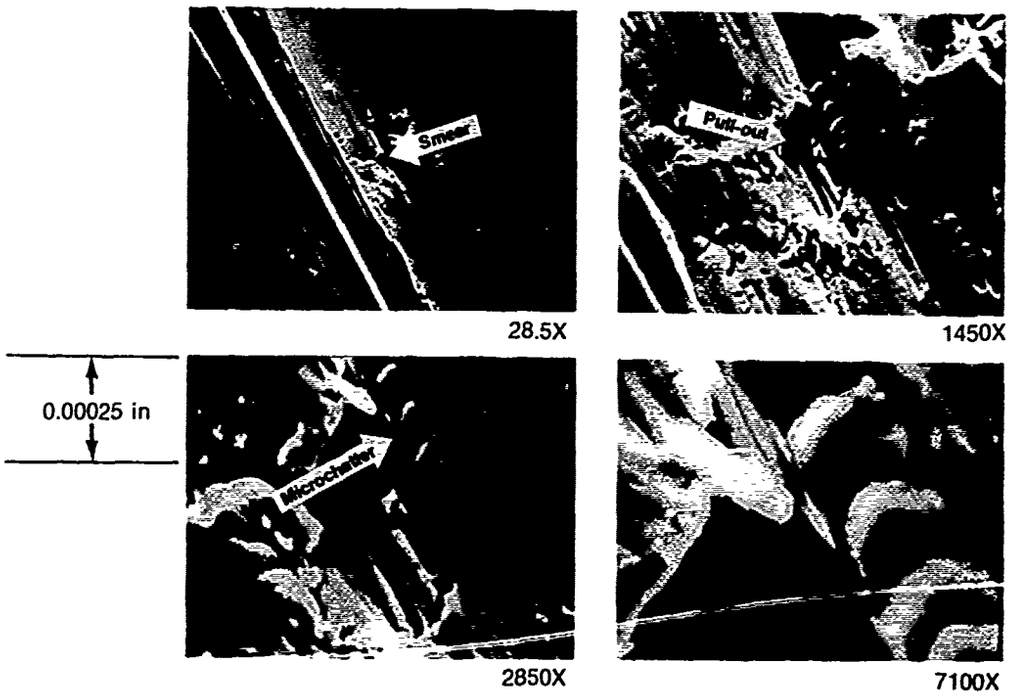


Figure 18.3–36 Turning Inconel Alloy 718 (solution treated and aged) with sharp tungsten carbide showing anomaly areas of smeared metal, material pull-outs and microchatter. Views at successively greater magnification from scanning electron microscope taken at 15° from perpendicular. Plastically deformed surfaces as seen in figure 18.3–37. (G. Bellows[17])

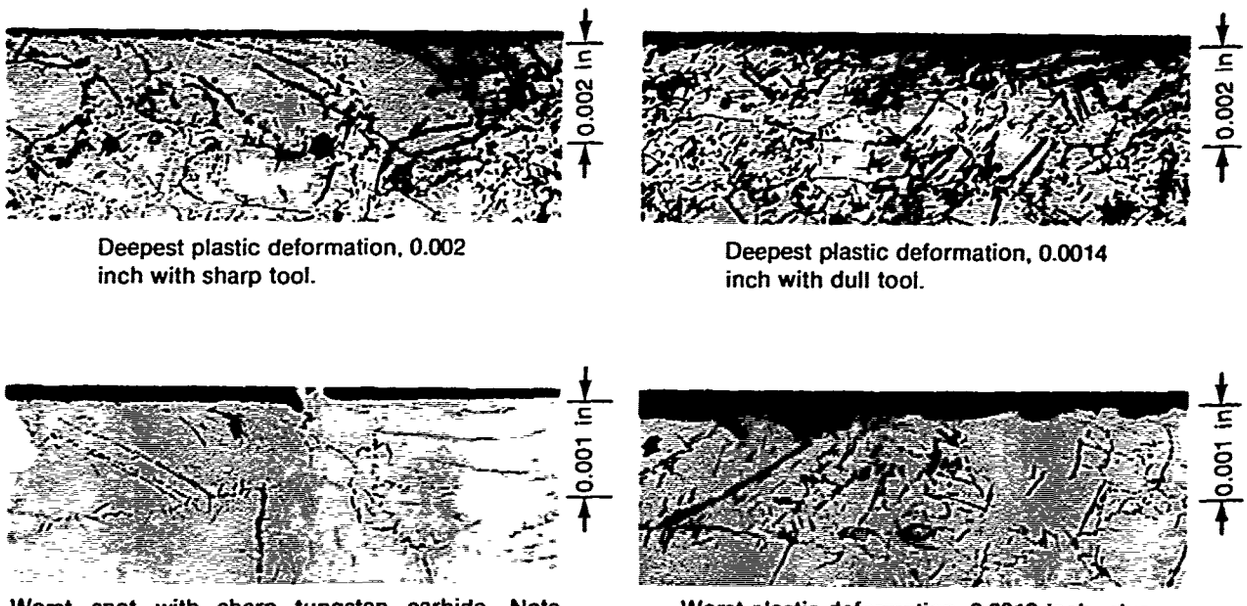


Figure 18.3–37 Surfaces produced by turning Inconel Alloy 718 (solution treated and aged) with sharp and dull tungsten carbide tools. Sharp tool had 0.005-inch wearland and dull tool had 0.013 inch. Surface roughness was 63 microinches R_a in both cases. (G. Bellows[17])

18.3 Surface Integrity

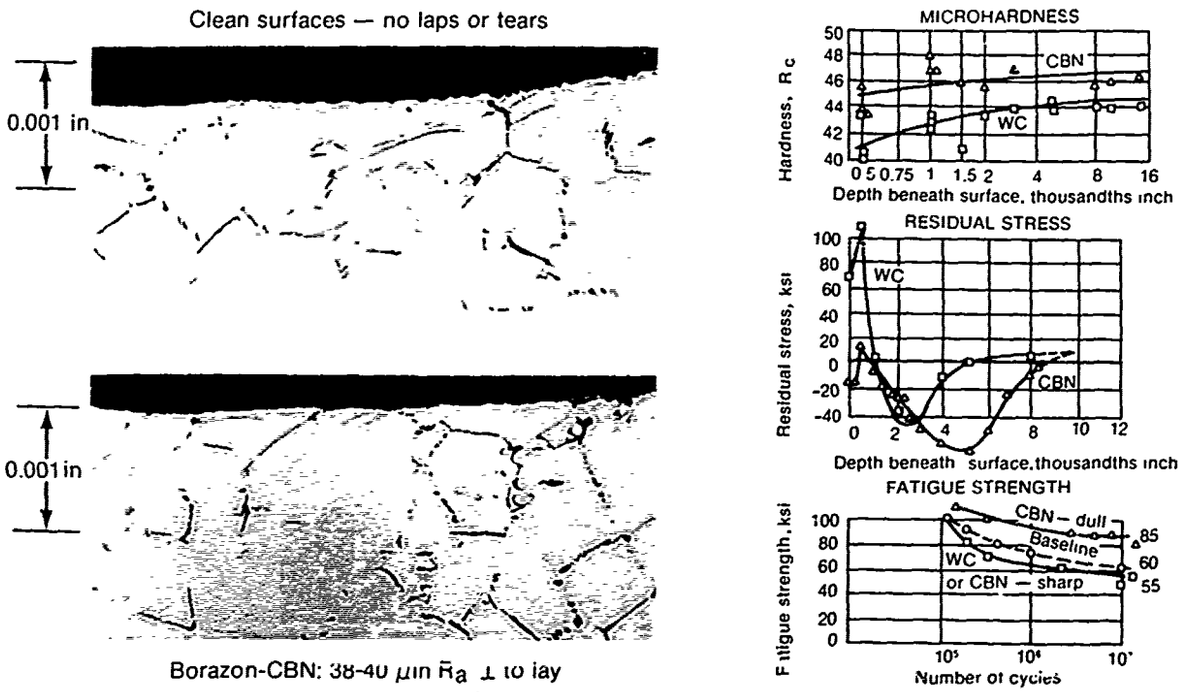


Figure 18.3–38 Turning Inconel Alloy 718 (solution treated and aged) standard surface integrity data set comparing performance of tungsten carbide tools with Borazon®-CBN. Baseline fatigue curve made with low-stress-ground specimens. (G. Bellows[17])

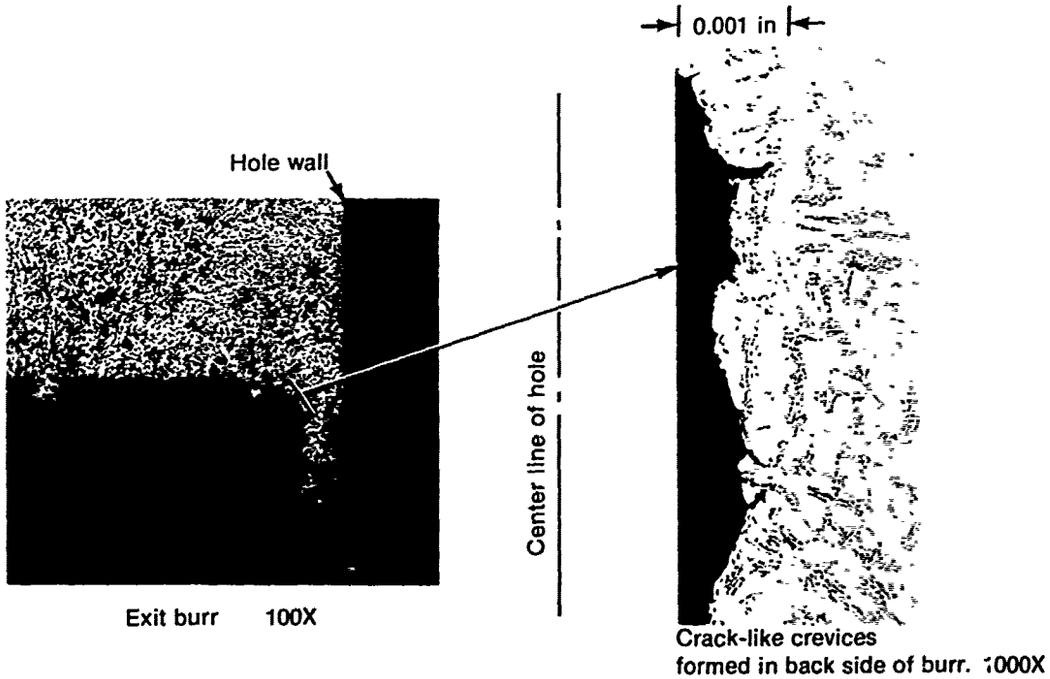
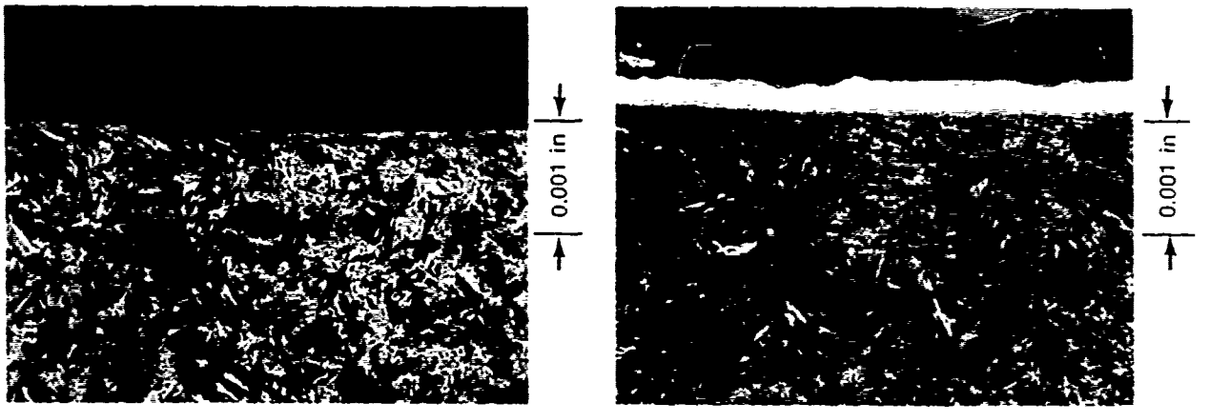
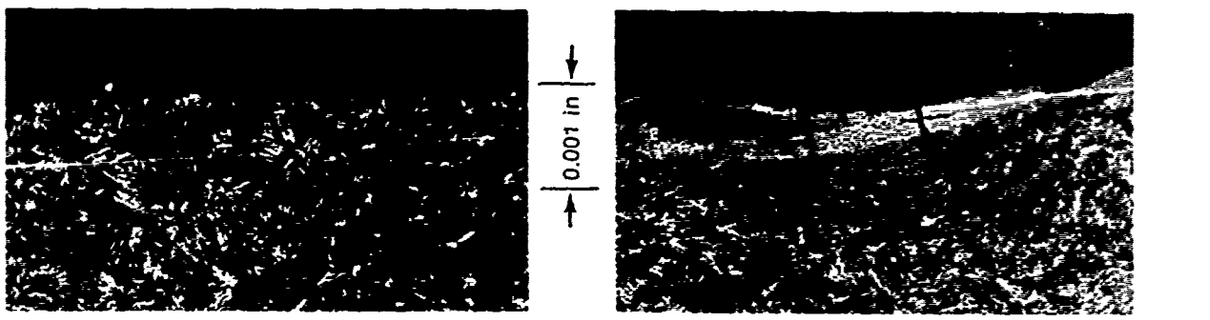


Figure 18.3–39 Drilling of Ti-6Al-6V-2Sn. *Right*, crack-like crevices commonly found in drilled and reamed holes. *Left*, the section shown is a burr on the workpiece surface. Burrs have been shown to be responsible for appreciable reduction of fatigue strength in steels and in titanium alloys.



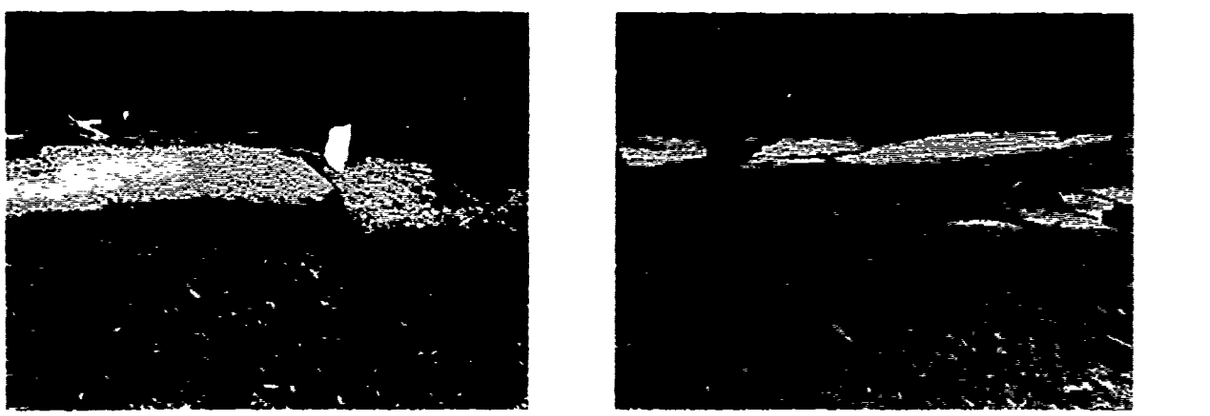
Sharp drill. 750X
Thin zone of plastic deformation at the surface.

Dull drill. 750X
Thin uniform layer of untempered martensite.



Sharp drill. 750X
No surface alteration.

Dull drill. 750X
Plastic deformation and extensive cracking.



Dull drill. 750X
Untempered martensite (62 R_C) plus surface cracking.

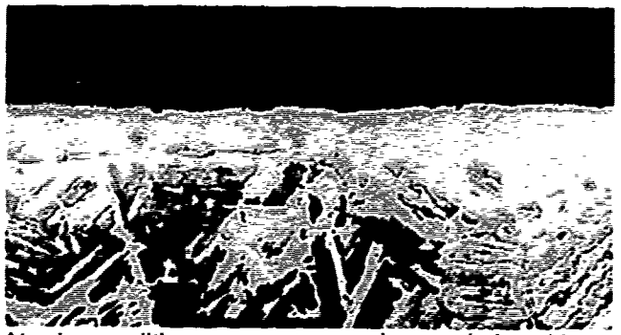
Dull drill. 750X
Extensive laps and tears.

Figure 18.3–40 Surfaces produced by drilling 4340 steel. Top two photos represent carbide drilling 4340 (quenched and tempered, 54 R_C); remaining photos represent high speed steel drilling 4340 (quenched and tempered, 48 R_C). (M. Field, W. P. Koster and J. B. Kohls[15])

18.3 Surface Integrity



Gentle conditions — very thin trace of cold work may be seen on the surface. 500X



Abusive conditions — an overaged or resolutioned layer 0.001-inch deep at 37 R_C is found on the surface. Total affected depth is approximately 0.002 inch. 500X

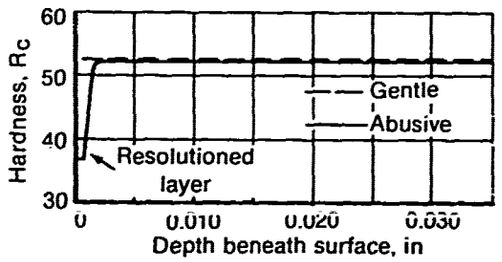
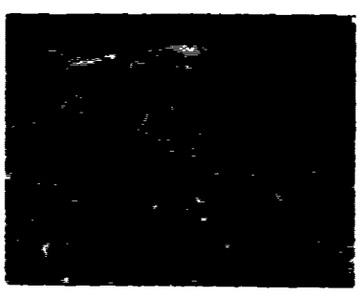


Figure 18.3–41 Surface characteristics of 18% nickel maraging steel Grade 250 (aged, 52 R_C) produced by drilling. (M. Field, W. P. Koster and J. B. Kohls[15])



Sharp reamer.
No surface alteration.

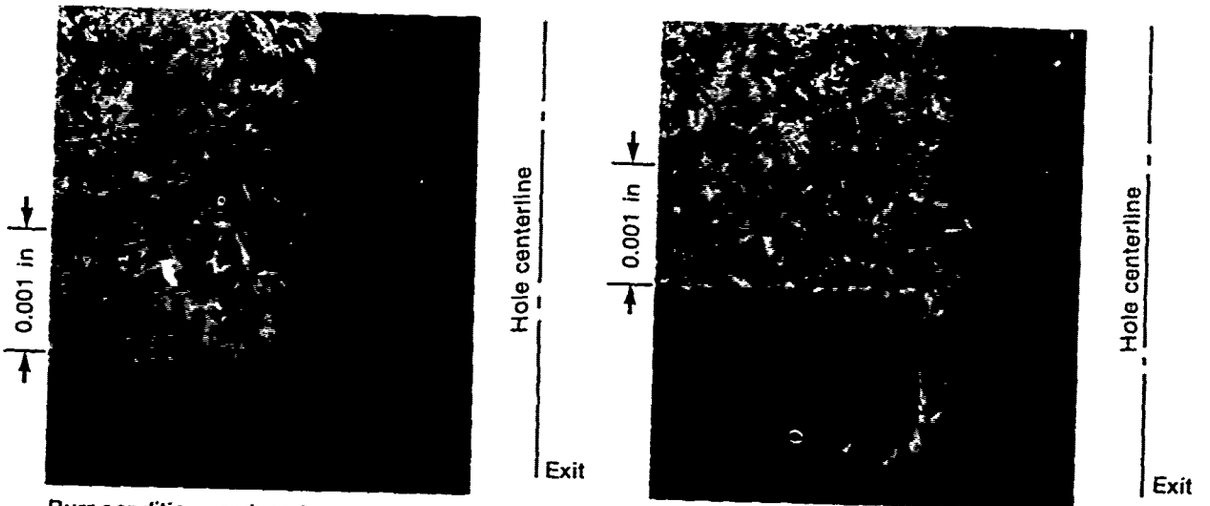


Dull reamer. 750X
Built-up edge resulting in surface tear.



Dull reamer. 750X
Short tears plus thin film of surface deformation.

Figure 18.3–42 Surfaces produced by high speed steel power taper reaming 4340 steel (quenched and tempered, 40 R_C). (M. Field, W. P. Koster and J. B. Kohls[15])

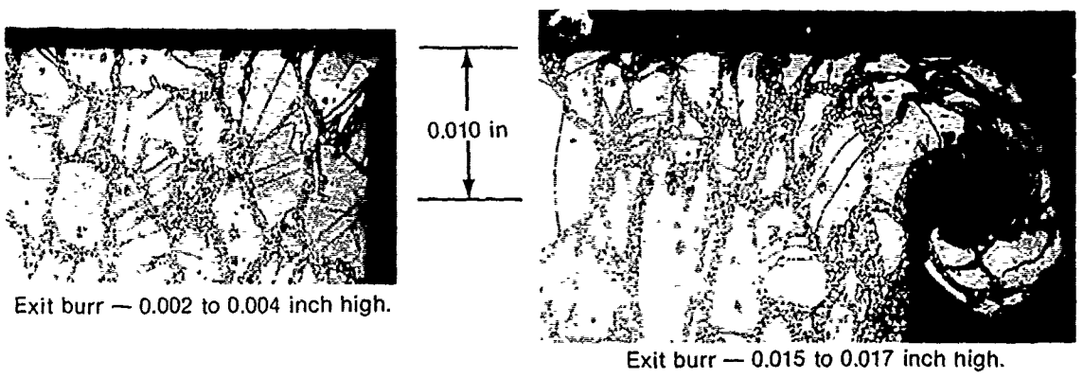


Burr condition produced by sharp reamer. 750X

Burr condition produced by dull reamer. 750X

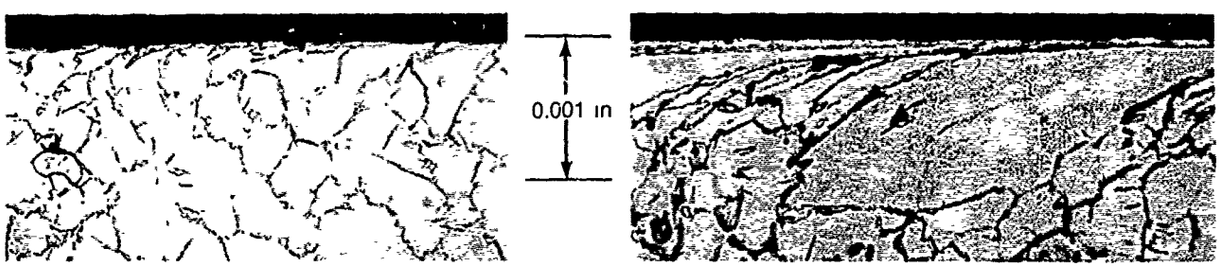
Figure 18.3–43 *Surfaces produced by high speed steel power taper reaming 4340 steel (quenched and tempered, 48 R_C).* (M. Field, W. P. Koster and J. B. Kohls[15])

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Exit burr — 0.002 to 0.004 inch high.

Exit burr — 0.015 to 0.017 inch high.



0.00045 Plastic deformation

0.0012 inch Plastic deformation and
0.0001 inch smeared metal.

INITIAL BROACHING PASS

LAST PASS, #254

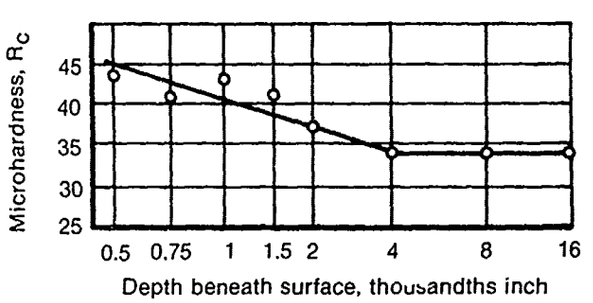


Figure 18.3-44 Broaching of Inconel Alloy 718 (solution treated and aged) with T15 high speed steel tools. Wearland increased to 0.006 to 0.007 inch during 254 cuts for a total of 158 inches of cut. Microhardness traverse taken after 254 passes. (Surface Integrity Encyclopedia[1])

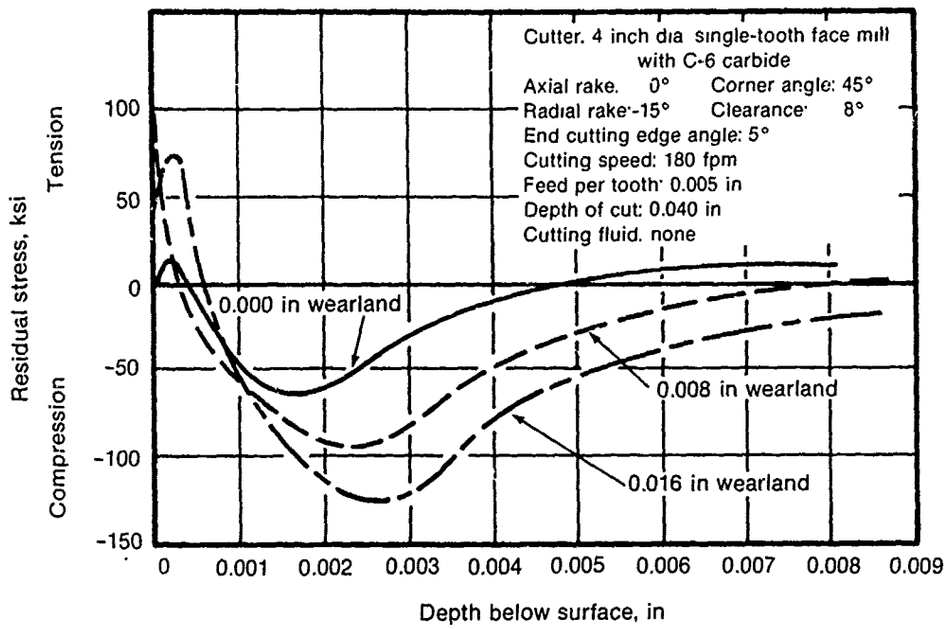


Figure 18.3–45 Effect of tool wear on residual stress in milled surface, face milling of 4340 steel (52 R_C). Note that the amount of residual compressive stress produced in this specimen is related to the tool sharpness. The worn tool produced a deeper compressive layer. (W. P. Koster and J. B. Kohls[18])

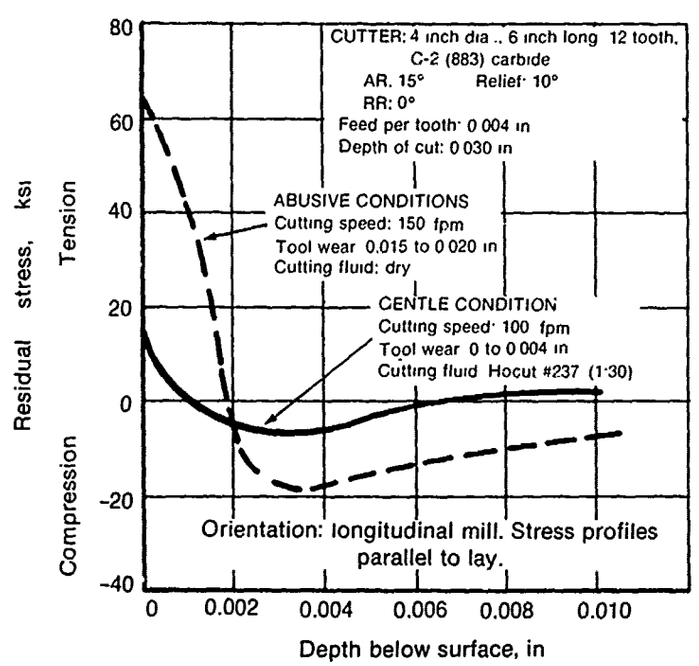


Figure 18.3–46 Residual surface stress profiles of Ti-6Al-6V-2Sn (solution treated and aged, 42 R_C) produced by peripheral end milling. (W. P. Koster and J. B. Kohls[18])

18.3 Surface Integrity

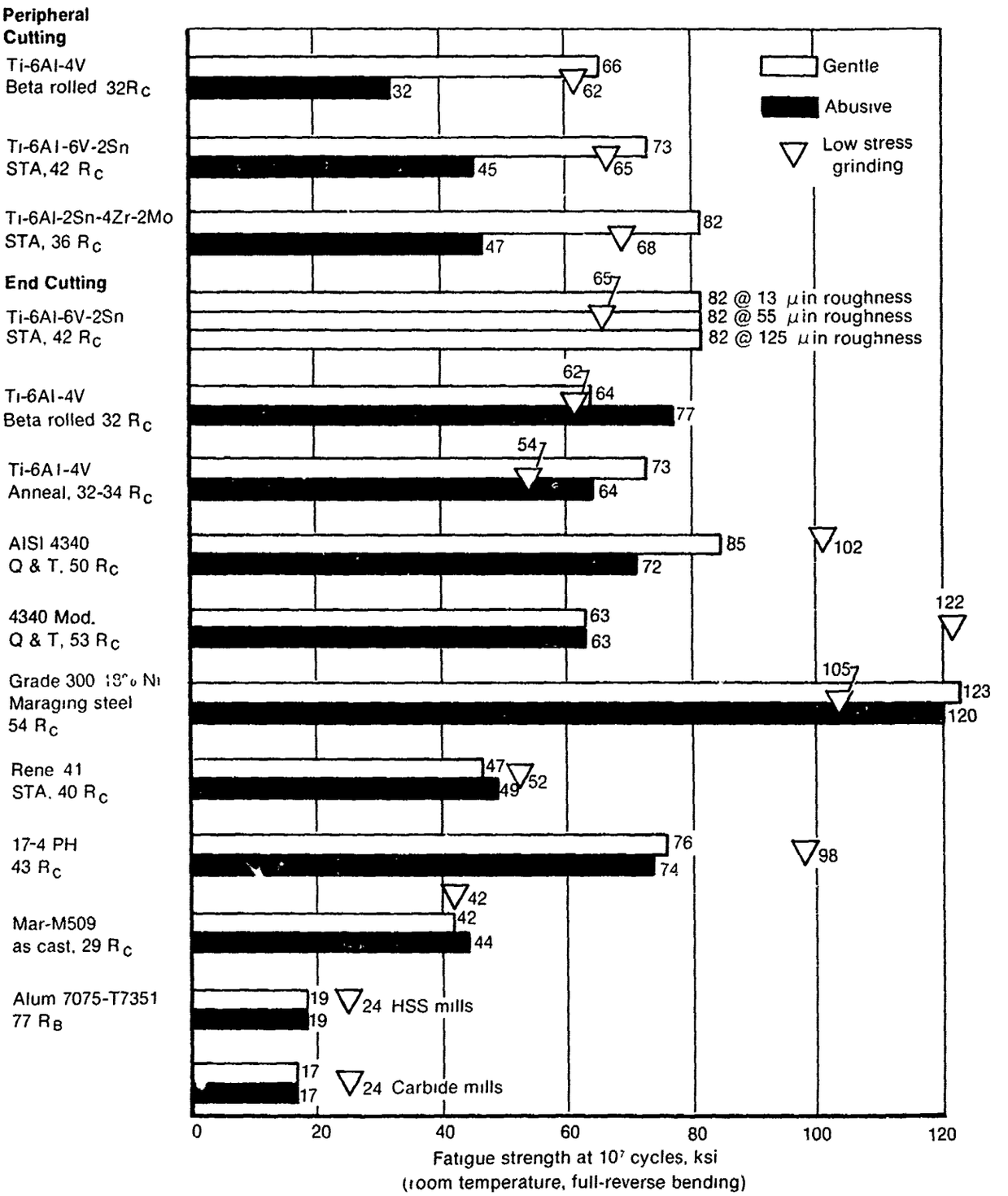


Figure 18.3-47 Summary of high cycle fatigue strength—end milling.

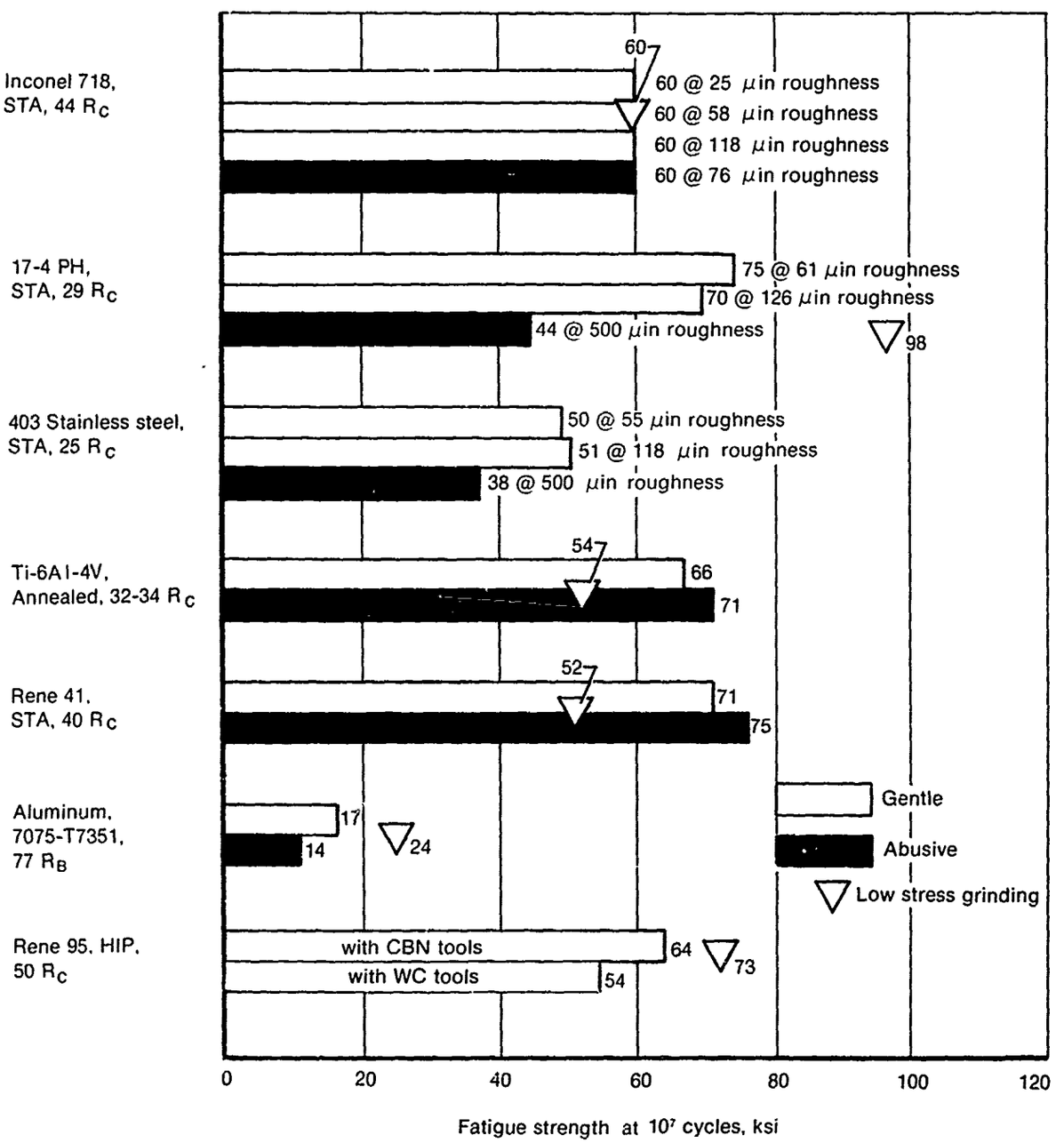


Figure 18.3-48 Summary of high cycle fatigue strength—face turning.

18.3 Surface Integrity

TABLE 18.3-10 Surface Integrity Effects Observed in Mechanical Material Removal Processes

PROPERTY AND TYPE OF EFFECT	FINISHING, "GENTLE" OR LOW STRESS CONDITIONS		ROUGHING, "OFF-STANDARD" OR ABUSIVE CONDITIONS	
Surface roughness·	μin R_a	μm R_a	μin R_a	μm R_a
Average range	8 to 63	0.2 to 1.6	125 to 250	3.2 to 6.3
Less frequent range	1 to 125	0.025 to 3.2	63 to 1,000	1.6 to 25
Mechanical altered material zones:	inch*	mm*	inch*	mm*
Plastic deformation (PD)	0.0017	0.04	0.0047	0.12
Plastically deformed debris (PD²)	***	***	***	***
Hardness alteration†	0.0010	0.025	0.0200	0.50
Microcracks or Macrocracks	0.0005	0.013	0.0015	0.04
Residual stress‡	0.0060	0.15	0.0140	0.36
Metallurgical altered material zones:	inch*	mm*	inch*	mm*
Recrystallization	—	—	—	—
Intergranular attack (IGA)	***	***	***	***
Selective etch, pits, protuberances	0.0004	0.01	0.0010	0.025
Metallurgical transformations	0.0015	0.04	0.0200	0.50
Heat-affected zone (HAZ) or Recast layer	0.0001	0.003	0.0030	0.076
High cycle fatigue (HCF):	percent		percent	
Variation from "handbook" values at room temperature§	−50 to +22		−48 to +2	

SOURCE: G. Bellows and J. B. Kohls.[20]

NOTE: A dash (—) in the table indicates no or insufficient data. A triple asterisk (***) in the table indicates no occurrences or not expected.

*Maximum observed depth normal to the surface.

†Depth to point where hardness becomes less than ±2 points R_c (or equivalent) of bulk material hardness (hardness converted from Knoop microhardness measurements).

‡Depth to point where residual stress becomes and remains less than 20 ksi [138 MPa] or 10% of tensile strength, whichever is greater.

§Handbook values from HCF testing frequently are generated from specimens that have been processed using low stress grinding, hand or gentle machine polishing or occasionally electropolishing. For this table, "handbook" values represent HCF strength values generated from low-stress-ground specimens (with their minor amount of retained but enhancing compressive residual stress). The values are the 10^7 cycle strengths from full-reverse bending tests at room temperature.

Specific Guidelines and Data for ABRASIVE Material Removal Processes

The heat in the workpiece surface resulting from the use of any of the varieties of abrasive machining is the principal ingredient affecting surface integrity. The amount of heat is proportional to the intensity with which the process is applied. The degree of surface effects is a function of the thermal properties of the workpiece material and its metallurgical response to the heating level. Residual stress and the attendant distortion can be problems, as can smeared metal or the debris from plastic deformation.

Grinding produces the greatest range of fatigue endurance sensitivity among the several material removal processes and alloys studied to date. Titanium alloys are the most drastically affected by grinding variables, although some cast nickel base materials are close behind. The ferrous materials, except the high strength varieties, are less sensitive to grinding variables than these other alloys groups, although very significant losses in fatigue strength are associated with both conventional and rough grinding levels of intensity. Even shallow, isolated spots of untempered or overtempered martensite can be detrimental to fatigue endurance strength. Hand sanding or deburring operations need strict control to reduce the human variables that can influence surface reliability. Abrasive cutoff operations are particularly susceptible to surface damage. Table 18.3-11 summarizes the surface integrity effects observed during the examination of several thousand pieces of data.

The charts and guidelines that follow have baselines the same as those for the mechanical material removal processes. Figures 18.3-49 through 18.3-54 illustrate good and poor surface effects from grinding. Figure 18.3-55 shows typical microhardness alterations, and figures 18.3-56 to 18.3-61 show variations of the residual stress or distortion patterns. High cycle fatigue responses are charted in figures 18.3-62 and 18.3-63. Other grinding illustrations are figures 18.3-1, 18.3-2, 18.3-8, 18.3-10, 18.3-13, 18.3-15, 18.3-17, 18.3-18, 18.3-21, 18.3-25, 18.3-26, and 18.3-28.

Abrasive Process Guidelines that Promote Good Surface Integrity Results

1. Low stress grinding techniques can reduce distortion and surface damage. Frequent coarse dressings of softer grade wheels, lower infeeds and reduced grinding wheel speeds with lubricating-type cutting fluids are the principal elements of low stress grinding. A shallow depth of low value tensile or compressive residual stress can be attained.

2. Higher work material speeds can aid both productivity and surface integrity. Lower wheel surface speeds aid surface integrity without sacrificing productivity.

3. Frequent coarse dressing of grinding wheels can reduce surface damage by keeping the wheels open and sharp, thus helping to reduce temperatures at the wheel-workpiece interface.

4. Modifications to established low stress grinding procedures should not be attempted unless testing confirms that they can be tolerated.

5. If low stress grinding is specified for finishing operations, then conventional grinding can be used to within 0.010 inch [0.254 mm] of the finished size, provided that the work materials are not sensitive to cracking.

6. Lubricating-type fluids and coolants should have a copious and positively directed flow and should be checked for their chemical action on the specific material being ground.

7. Conventional grinding conditions should not be used for finish grinding of highly sensitive alloys such as high strength steels, high temperature nickel and cobalt base alloys, and titanium or molybdenum alloys.

8. The heat-affected zones from rough grinding can be much deeper than the surface discolorations might indicate. Microhardness traverses can generally detect the depth of surface alterations.

9. High stress grinding of martensitic steels can create untempered martensitic zones with overtempered martensitic zones below them, both of which will limit fatigue strength.

10. Crack detection tests should be made when rough grinding materials. Existing surface cracks can propagate ahead of the grinding when finishing some thermally sensitive materials. Low stress grinding should be used to remove more than the altered material zones from any prior conventional grinding operation.

11. Hand grinding of sensitive alloys should be discouraged, unless done under very careful control.

12. Strict instructions and controls over power hand sanders should be maintained.

13. Abrasive cutoff frequently has a harsh and deep surface effect, and these altered layers should be removed by more gentle processes.

14. Surface X-ray residual stress measurements can be misleading. A full profile is best, or enough checks should be made below the surface to correct for penetration of the X-rays and the slope of the profile.

15 Good dressing action on the grinding wheel is promoted by cleanliness and sharpness of the dressing tool. Pauses or dwells in the dressing tool action can dull the wheel surface, particularly with the roll form, crush roll or form block dressing tools.

Special Comments Concerning Surface Integrity Practices for Abrasive Machining Processes

Reduce grinding distortion and surface damage by using "low stress" conditions during finish grinding. Conventional finish grinding practices should be replaced by low stress grinding procedures in order to minimize grinding distortion and to reduce the possibility of producing extensive surface metallurgical alterations and cracking. Low stress grinding procedures are described in table 18.3-12. Some of the metallurgical alterations caused by abusive grinding do not produce cracking immediately, but they develop conditions leading to delayed cracking, which may occur later "on the shelf" or prematurely in service, thereby seriously complicating inspection practices. Low stress grinding in comparison with conventional practices employs softer grade grinding wheels, reduced grinding wheel speeds, reduced infeed rates, and chemically active cutting fluids. Low stress conditions should be used for removing the last 0.010 inch [0.254 mm]. See tables 18.3-13 to 18.3-17.

Modification of low stress grinding procedures should not be attemped unless service experience or testing programs in the shop and/or laboratory confirm that compromises can be tolerated. For certain type parts made of sensitive alloys, no compromises should be permitted in the specification of low stress grinding parameters. Experience has shown that it is sometimes possible to relax low stress procedures in order to accommodate equipment limitations or to increase production rates. Table 18.3-17 is an example of a set of grinding conditions, case A, which produced scrap as a result of grinding cracks in the fir-tree section of IN-100 turbine blades. Substitution conditions, case B, are essentially low stress except for the infeed. Experience had indicated that in this instance an infeed as high as 0.002 inch [0.050 mm] could be tolerated.

An almost identical cracking problem was encountered in the production of Inconel Alloy 713C turbine blades. This problem was also solved by implementation of the recommendations shown for case B of table 18.3-17. Parts made of cast HS-31 and cast WI-52 have also cracked in conventional grinding. Because of these experiences and the lack of other data, it is suggested that all cast nickel and cast

cobalt base high temperature alloys be processed using low stress grinding conditions for the highly stressed or critically loaded surfaces.

If low stress grinding is required for finish grinding, then conventional grinding can be used to within 0.010 inch [0.254 mm] of finish size if the materials being ground are not sensitive to cracking. During *conventional grinding*, metallurgical alterations, including stresses, are usually confined to within approximately 0.005 inch [0.127 mm] of the surface or less. This makes it possible to remove most of the stock by conventional practices and then finish grind using low stress methods. However crack detection tests should be made to see that conventional grinding of the material in question does not create cracks of greater depth. Stock allowances of the order of 0.010 inch [0.254 mm] or greater, if necessary, are suggested to compensate for location inaccuracies in holding fixtures.

Finish grinding of critical and/or highly stressed surfaces of sensitive alloys exposed to high service stresses should be performed using low stress grinding instead of conventional grinding. Some high performance, high strength alloys are also sensitive to the thermal shocks accompanying grinding. A partial list of these alloys is as follows:

High Strength Steels, Wrought
- 4340 or 4340 Mod. at 40–54 R_C
- 300M or D6ac at 48–56 R_C
- Maraging Steels
- HP9-4-45

High Temperature Nickel and Cobalt Base Alloys, Wrought
- Rene 41
- Rene 80
- Udimet 700
- AF 95 (Rene 95)
- Waspaloy
- AF2-1DA
- Inconel Alloy 718
- Rene 125

Titanium Alloys, Wrought
- Ti-6Al-4V
- Ti-5Al-2.5Sn
- Ti-6Al-2Sn-4Zr-2Mo
- Ti-6Al-6V-2Sn

Table 18.3-18 and figure 18.3-62 provide high cycle, room temperature fatigue data showing the adverse effects of abusive and of conventional grinding compared with gentle or low stress grinding for several classes of aerospace materials.

Fatigue strength reduction of martensitic steels as a result of abusive grinding has been determined to be approximately equal, regardless of the quantity of untempered martensite (UTM) or overtempered martensite (OTM) present. Traces of UTM or OTM as well as 0.004-inch [0.10 mm] deep layers were associated with the same fatigue strength reduction, figure 18.3-25. Reduction of the fatigue strength was found to be about 30 to 35 percent. For quenched and tempered steels, OTM is frequently produced under the UTM. Even if the UTM is removed by gentle grinding, the fatigue strength is still reduced 25 to 30 percent. This indicates that overtempered martensite may be as important as untempered martensite in influencing fatigue strength.

Conventional grinding conditions should not be employed for either roughing or finishing alloys which are ultra-sensitive to the grinding process. From experience, certain alloys have been found to crack easily during conventional grinding. For such alloys, it is likely that the cracks created will not be eliminated by finish grinding. The high temperature nickel and cobalt base *cast* alloys (such as IN-100, Inconel Alloy 713C, MAR-M509, HS-31, WI-52, Udimet 500, Udimet 700, Inconel Alloy 738, etc.), in contrast with the *wrought* nickel and cobalt base high temperature alloys, are examples of alloys which should never be ground conventionally. See table 18.3-17 for a specific case history involving cracking of a cast nickel base high temperature alloy. Metals and alloys which are brittle, such as beryllium and tungsten, tend to respond similarly.

Frequent dressing of grinding wheels can reduce surface damage by keeping the wheels open and sharp, thus helping to reduce temperatures at the wheel-workpiece interface. Automatic dressing and wheel compensation contribute to the economic feasibility of frequent dressing. Crush dressing and diamond roll dressing can also be used to minimize the cost of frequent dressing.

Cutting fluids, properly applied, help promote surface integrity. In order to get fluid to the wheel-workpiece interface, position the fluid nozzle as close to the wheel as possible. A general rule of thumb, regarding the quantity of fluid needed, is to use at least two gallons of fluid per horsepower per minute.

Hand grinding of sensitive alloys should be discouraged. The inherent lack of control has been responsible for creating many surface defects.

Abrasive cutoff requires special surface integrity considerations. Abrasive cutoff operations generally cause deeper surface alterations than grinding, sometimes as much as 0.050 inch [1.27 mm], and capability for minimizing damage from cutoff operations varies from plant to plant. It is recommended, therefore, that when abrasive cutoff is used that steps be taken to determine the extent of the disturbed layers and proper stock allowances be made for subsequent cleanup by suitable machining. Also, the entire cut surface should be examined because the temperatures generated are subject to extreme variation across the cut.

Controls for hand power sanders should be maintained. Test data reported in figure 18.3-63 show that good fatigue results can be obtained for such alloys as 4340 at 50 R_C and Ti-6Al-4V provided that controlled conditions are maintained. The conditions are as follows:

Use a low belt speed (2000 feet per minute [10 m/s] maximum, for example).

Use a flexible (rubber) support for sanding disks or belts.

Use an abrasive grit generally no coarser than 80, and use coolant if feasible.

At present, the relatively new high speed grinding processes should not be used for finishing of highly stressed structural parts unless an extended data set is developed. Presently, insufficient mechanical property data are available to justify the recommendation of high speed grinding for critical parts even though increased production rates are attainable. High speed grinding increases the difficulty of the effective application of the grinding fluid, especially on complex parts, thereby making it more difficult to avoid surface damage from overheating.

Abrasive processing and especially finish grinding must be accomplished under strict process control when employed for the manufacture of aerospace components. Tests have shown that uncontrolled abusive as well as conventional grinding can decrease substantially the low and high cycle fatigue strengths at room and at elevated temperatures for titanium alloys, nickel base high temperature alloys and high strength steels. In addition to the room temperature high cycle fatigue data shown in table 18.3-18 and figure 18.3-62, data have been developed for elevated temperature high cycle fatigue and for low cycle fatigue. Tests on AF 95 (Rene 95) show that at 1000F [538C] the endurance limit (10^7 cycles, full-reverse bending) is lowered from 98 ksi [676 MPa] for gentle grinding to 48 ksi [331 MPa] for abusive grinding. Low cycle fatigue properties are affected adversely by abusive grinding, as shown in table 18.3-19.

Adjustment of the grinding conditions can substantially alter the surface conditions. When it is not possible or practical to control one of the operating parameters to low stress values, alteration of all of the other parameters to the best values can frequently achieve the desired surface quality, as shown in figure 18.3-64.

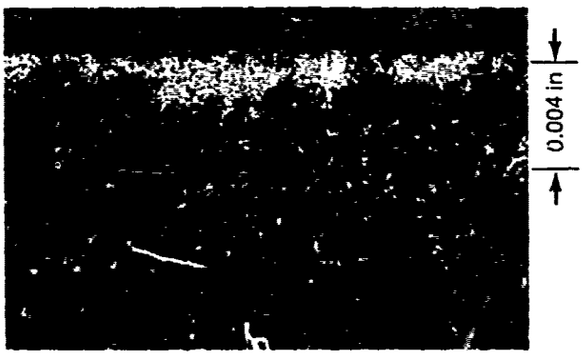
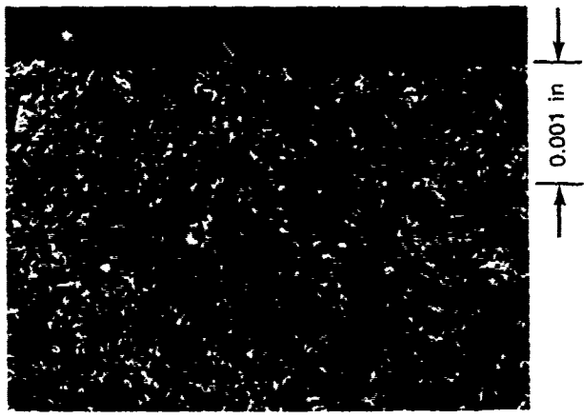


Figure 18.3-49 Surface produced by abusive grinding of 4340 steel (50 R_C). The thin white martensitic layer in the photomicrograph is often found in the surfaces of hardened alloy steels after grinding. It has been found that even isolated patches of untempered or overtempered martensite as thin as 0.0002 inch can reduce fatigue strength of high strength steels as much as 35% to 40%.

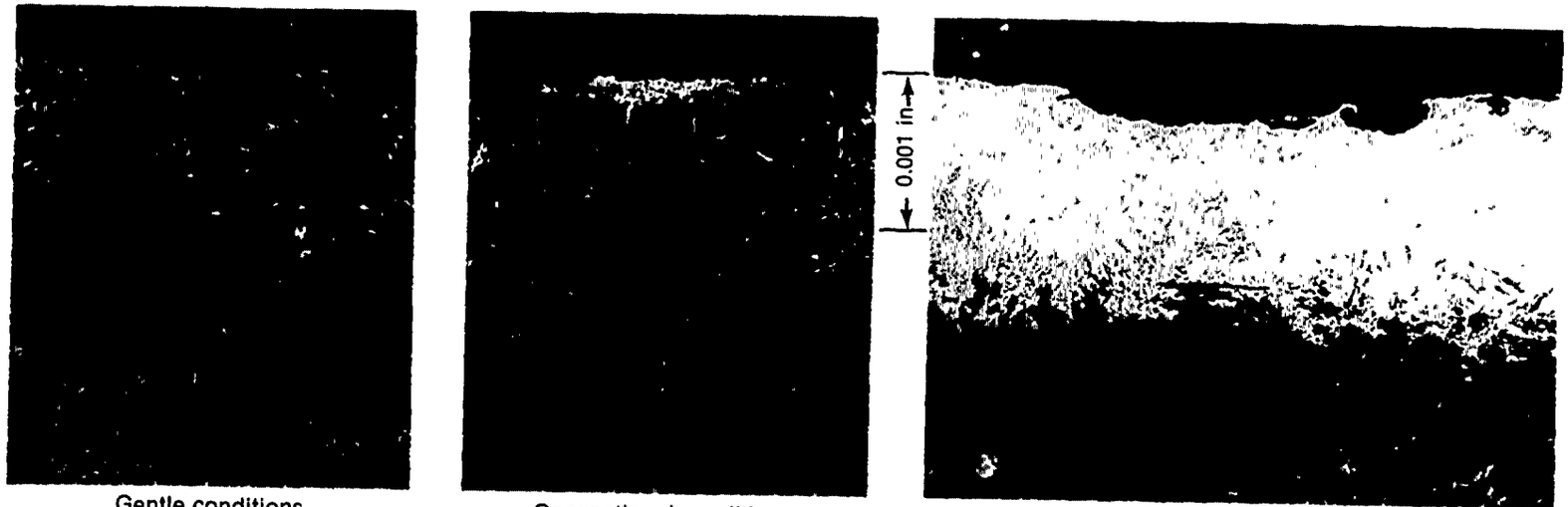


Infeed: 0.010 in/min
Surface roughness: 11 rms 1000X



Infeed: 4.9 in/min
Surface roughness: 160 rms 1000X

Figure 18.3-50 Surfaces produced by plunge grinding 4340 steel (45 R_C). Grinding Wheel: 32A54MVBEX113. Wheel Speed: 11,500 fpm. (M. Field[19])



Gentle conditions
Surface roughness: 45 μin R_a

Conventional conditions
Surface roughness: 40 μin R_a

Abusive conditions
Surface roughness: 50 μin R_a

Gentle grinding produced no visible surface alterations. Conventional grinding shows evidence of spotty surface rehardening and underlying overtempering or softening. Abusive grinding produced a rehardened surface layer averaging 0.001 inch deep and an underlying overtempered zone approximately 0.004 inch deep.

1000X

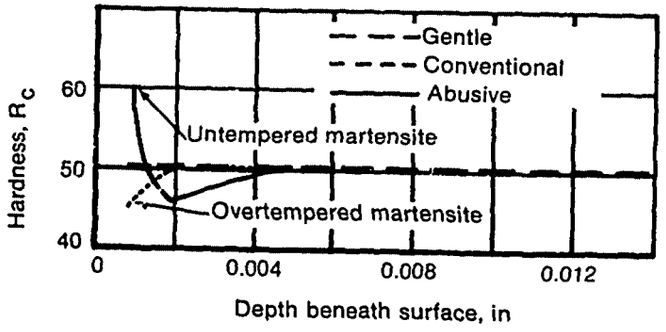
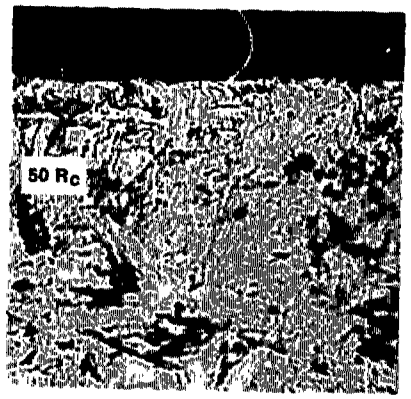


Figure 18.3–51 Surface characteristics of 4340 steel (quenched and tempered, 50 R_c) produced by surface grinding. (See figure 18.3–18 for residual stress values corresponding to these section views and figure 18.3–13 or 18.3–62 for fatigue test results.) (W. P. Koster et al[8])



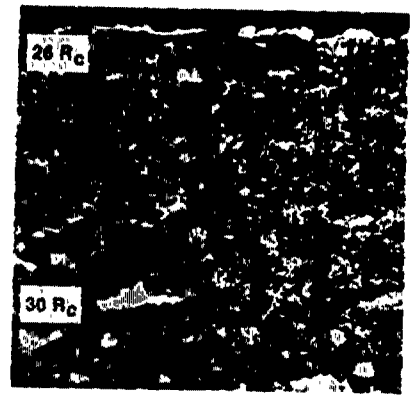
(a)

1018 steel finished by gentle (a) and abusive grinding (b). Note the disturbed and work-hardened layer produced by the abusive procedure



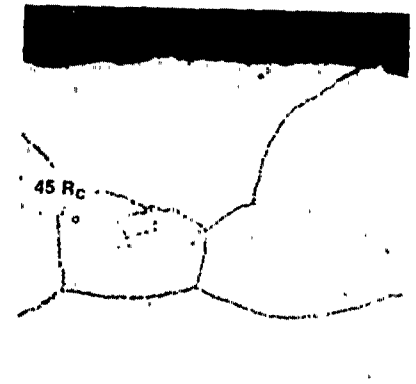
(c)

Quenched and tempered 410 stainless steel (50 R_C) showing slight disturbance produced by gentle grinding (c). A re-hardened layer plus an overtempered zone totalling 0.020 inch deep were produced by abusive grinding (d).



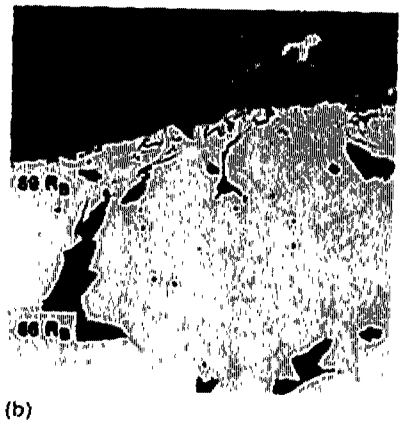
(e)

Aged Ti-6Al-4V exhibiting shallow white layer due to gentle grinding (e) and deeper distorted white layer 0 005 inch deep caused by abusive grinding (f).

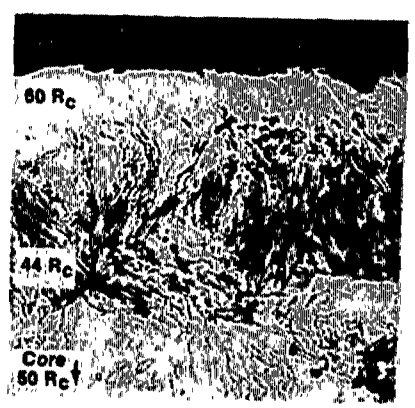


(g)

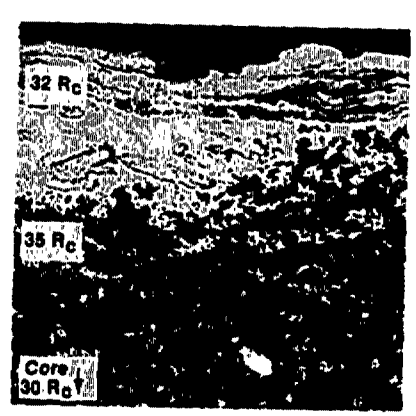
Waspaloy sample showing no surface effect due to gentle grinding (g) Abusive grinding (h) shows evidence of surface distortion and a dislodged grain at the surface



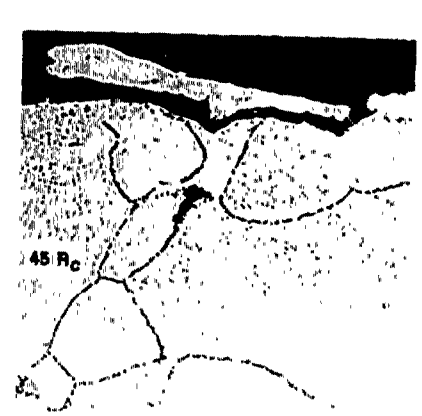
(b)



(d)



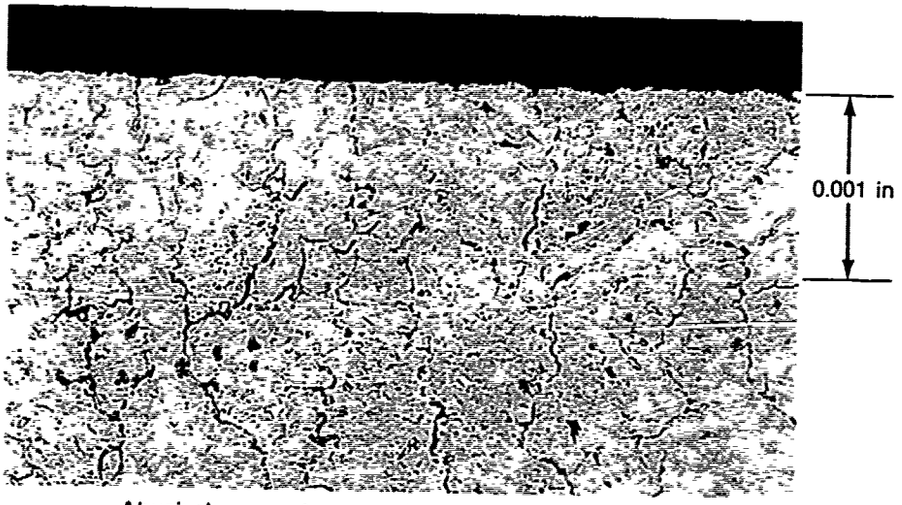
(f)



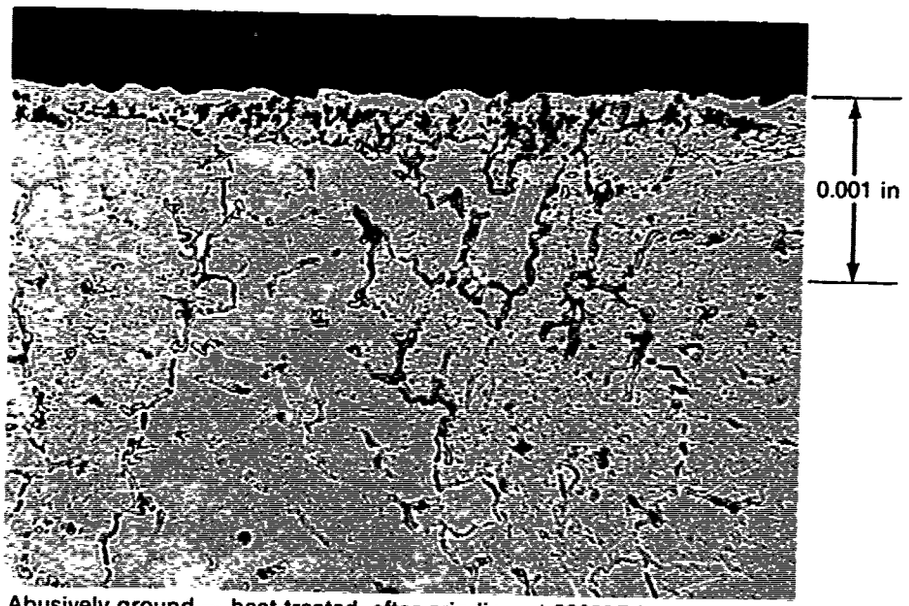
(h)

Figure 18.3–52 Surfaces of alloys produced by surface grinding.

18.3 Surface Integrity



Abusively ground — no subsequent heat treatment.



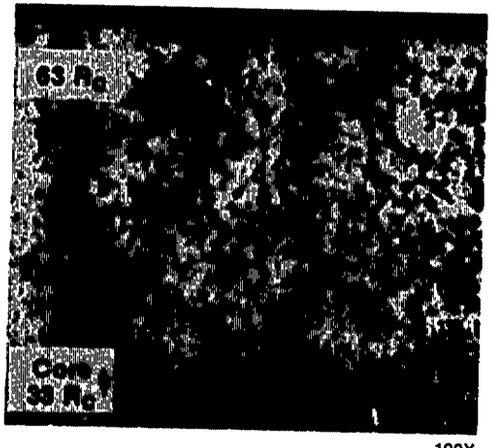
Abusively ground — heat treated, after grinding, at 2000°F for one vacuum. Recrystallized layer at surface.

Figure 18.3-53 Recrystallization resulting from abusive grinding of HS-31 alloy.



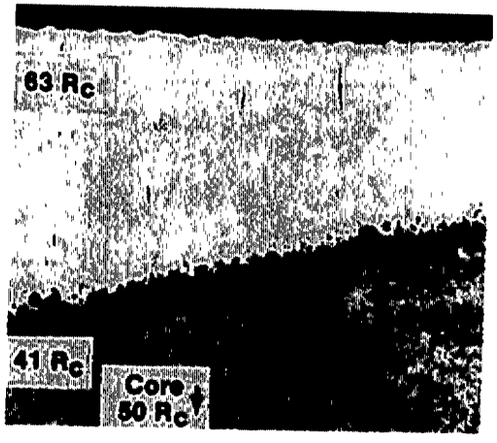
1000X

1018 steel showing partially re-austenitized pearlite which extends to a depth of about 0.005 inch.



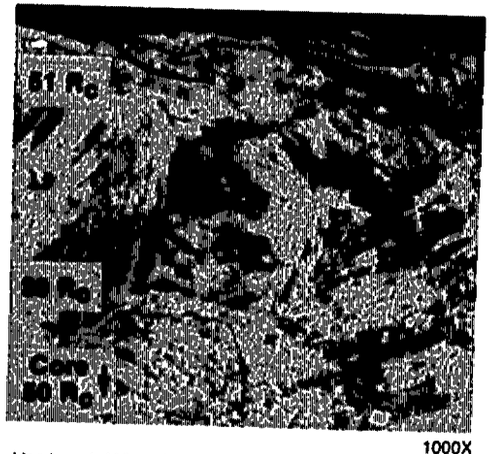
100X

Annealed 4340 steel showing re-hardened layer 0.003 inch deep.



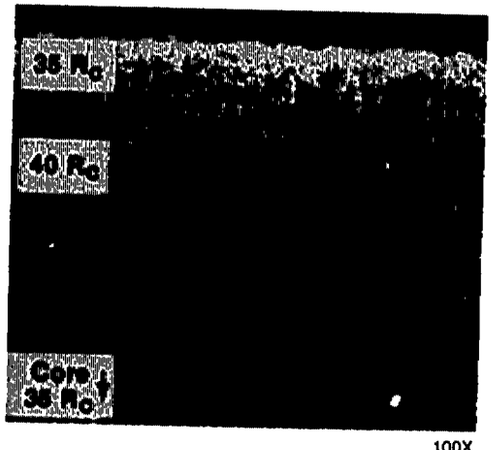
100X

Hardened 4340 steel (50 R_C) showing re-hardened surface zone and overtempered layer beneath. Total effect reached 0.050 inch.



1000X

Hardened 410 stainless (50 R_C) showing re-hardened surface and overtempered sub-zone. Total depth affected approached 0.090 inch.



100X

Ti-6Al-4V aged (33 R_C) showing re-solutioned alpha and general heat-affected structure. Total visible effect was 0.030 inch.



1000X

Waspaloy, which showed little or no microhardness or structural change.

Figure 18.3–54 Surfaces of alloys produced by an abrasive cutoff operation.

18.3 Surface Integrity

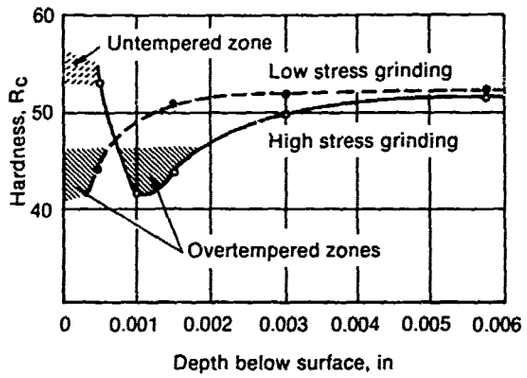


Figure 18.3–55 Typical hardness alteration traverses of subsurfaces as a result of grinding 4340 steel (quenched and tempered, 53 R_C) at low stress and high stress levels. (G. Bellows[13])

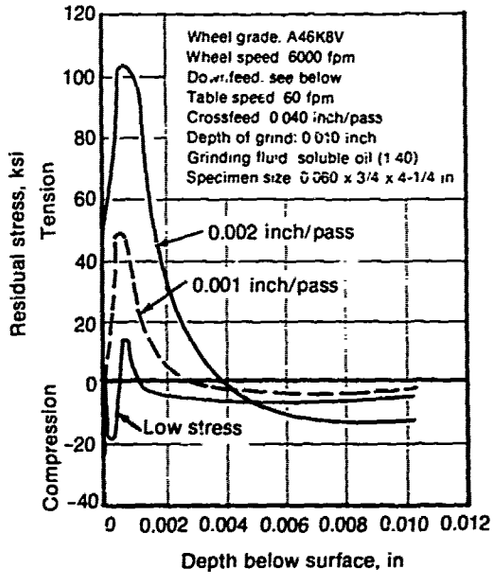


Figure 18.3–57 Effect of downfeed on residual stress in ground surface of 4340 steel (52 R_C). It should be noted that high residual tensile stresses are reduced by grinding at lower wheel speeds and at lower downfeeds. The corresponding distortions (measured at the center of a 0.060 inch by 3/4 inch by 4-1/4 inch specimen) are shown in figures 18.3–59 and 18.3–60. (M. Field, W. P. Koster and J. B. Kohls[15])

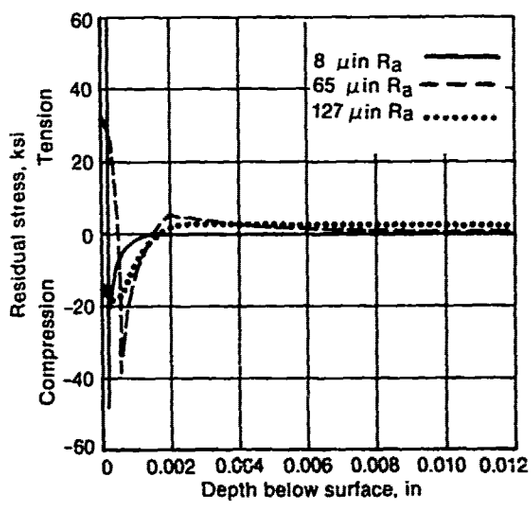


Figure 18.3–56 Residual stress profiles of 4340 steel (quenched and tempered, 50 R_C) for various values of surface roughness. Stress profiles and grinding lay parallel to longitudinal axis of specimens. (G. Bellows[13])

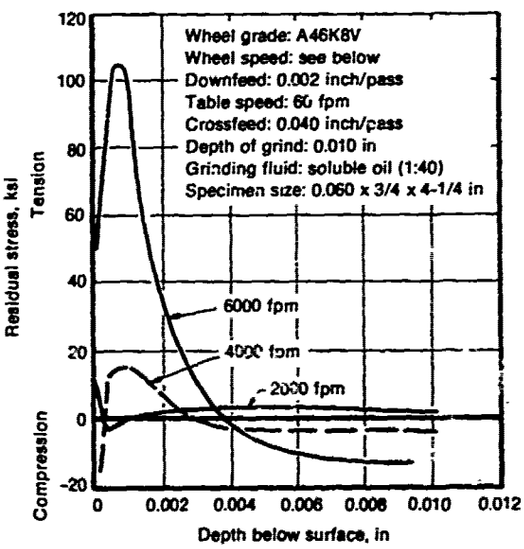


Figure 18.3–58 Effect of wheel speed on residual stress in ground surface 4340 steel (52 R_C). It should be noted that high residual tensile stresses are reduced by grinding at lower wheel speeds and at lower downfeeds. The corresponding distortions (measured at the center of a 0.060 inch by 3/4 inch by 4-1/4 inch specimen) are shown in figures 18.3–59 and 18.3–60. (M. Field, W. P. Koster and J. B. Kohls[15])

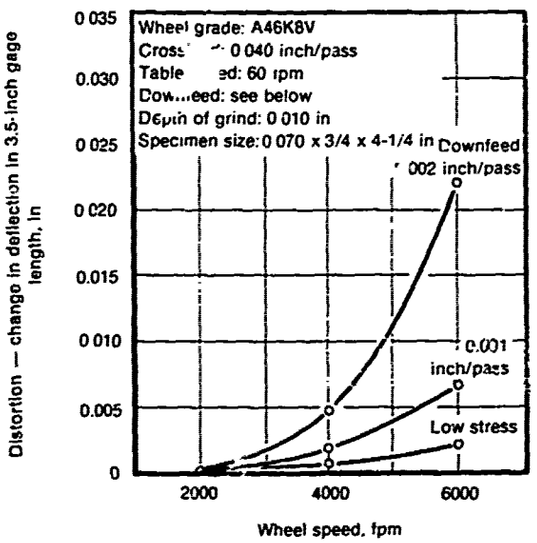


Figure 18.3–59 Effect of downfeed on change in deflection versus wheel speed when surface grinding 4340 steel (52 R_C). Note the low distortion produced by low wheel speed and low stress downfeed. A typical low stress downfeed calls for careful control in removal of the last 0.010 inch in finishing. The first 0.008 inch is taken at 0.0005 inch/pass and the last 0.002 inch at 0.0002 inch/pass. Residual stress values for these tests are shown on figures 18.3–57 and 18.3–58. (M. Field, W. P. Koster and J. B. Kohls[15])

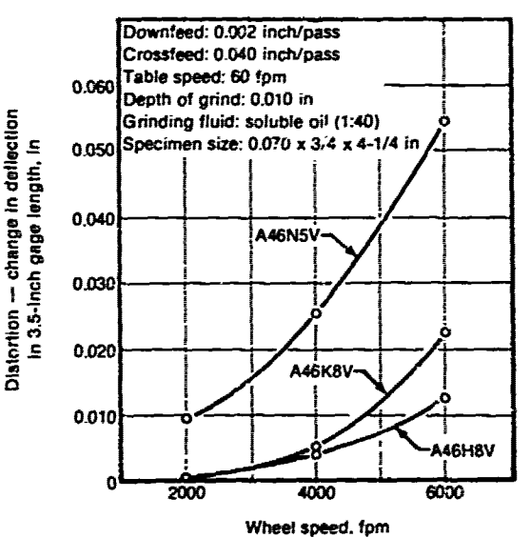


Figure 18.3–60 Effect of wheel grade on change in deflection versus wheel speed when surface grinding 4340 steel (52 R_C). Note that low wheel speeds and soft wheels tend to minimize distortion. Residual stress values for these tests are shown on figures 18.3–57 and 18.3–58. (M. Field, W. P. Koster and J. B. Kohls[15])

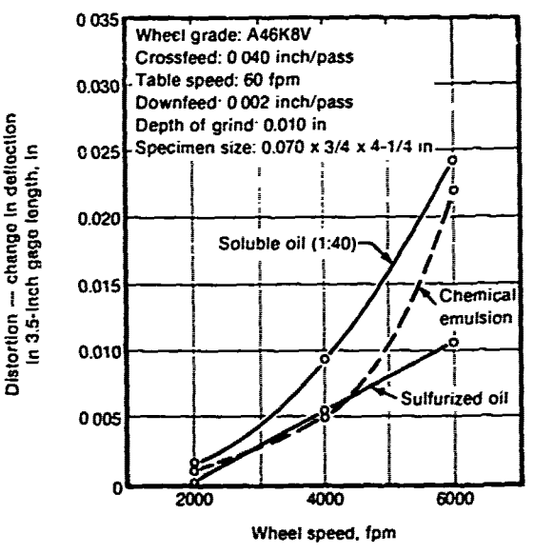


Figure 18.3–61 Effect of grinding fluid on change in deflection versus wheel speed when surface grinding 4340 steel (52 R_C). Distortion is minimized by use of low wheel speeds and also by using sulfurized oil. (M. Field, W. P. Koster and J. B. Kohls[15])

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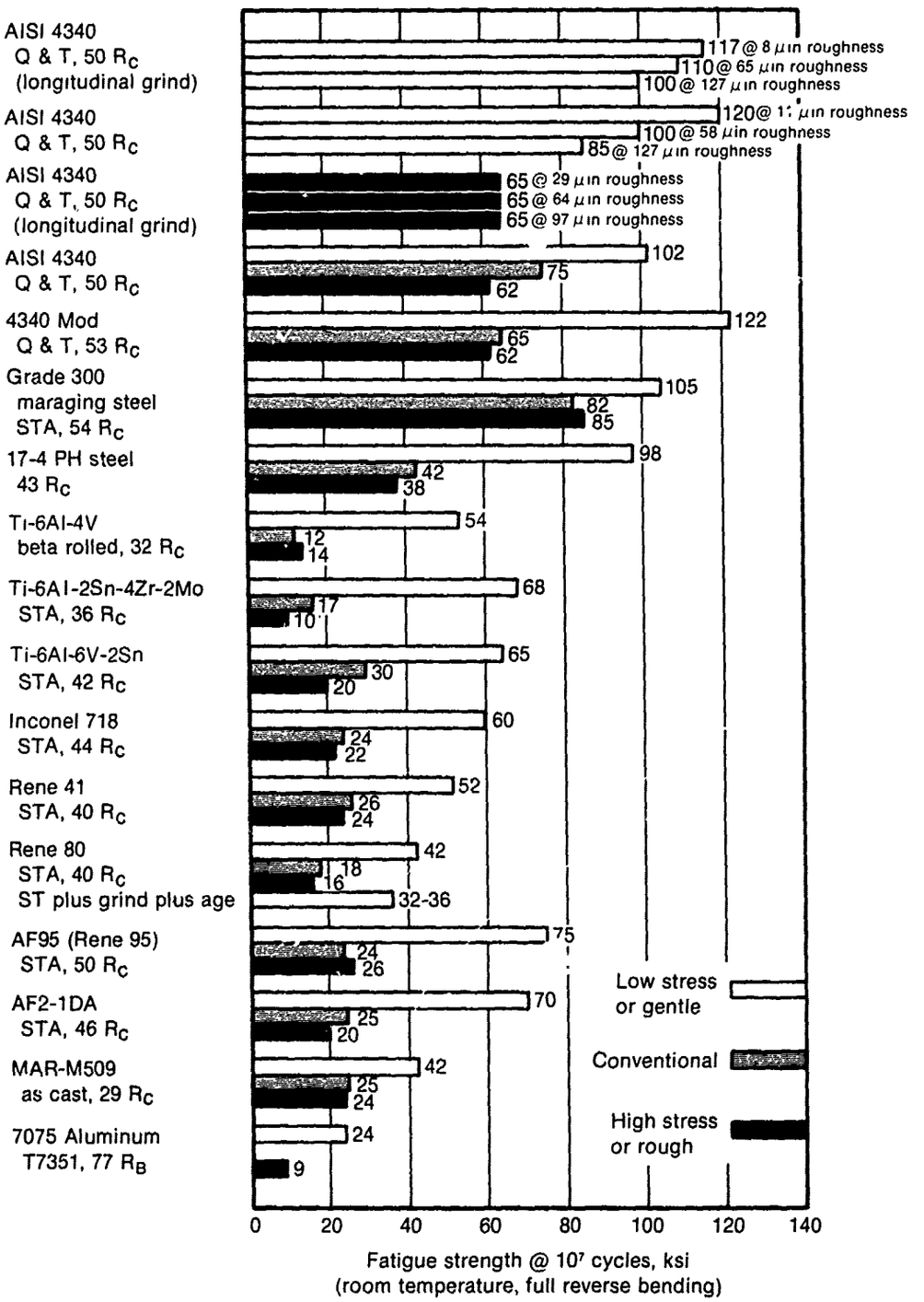


Figure 18.3-62 Summary of high cycle fatigue strength—surface traverse grinding.

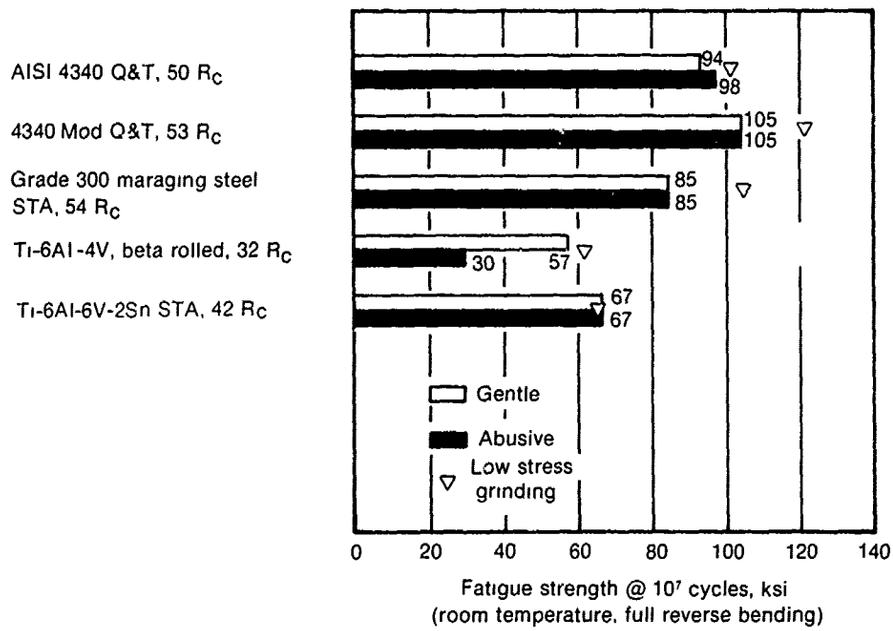


Figure 18.3-63 Summary of high cycle fatigue strength—hand sanding. Controlled hand grinding or hand sanding generally results in fatigue strength levels only slightly lower than those produced by gentle or low stress grinding. With one exception, the materials studied were not sensitive to variations in hand sanding processes over the range studied. (G Bellows and W. P Koster[16])

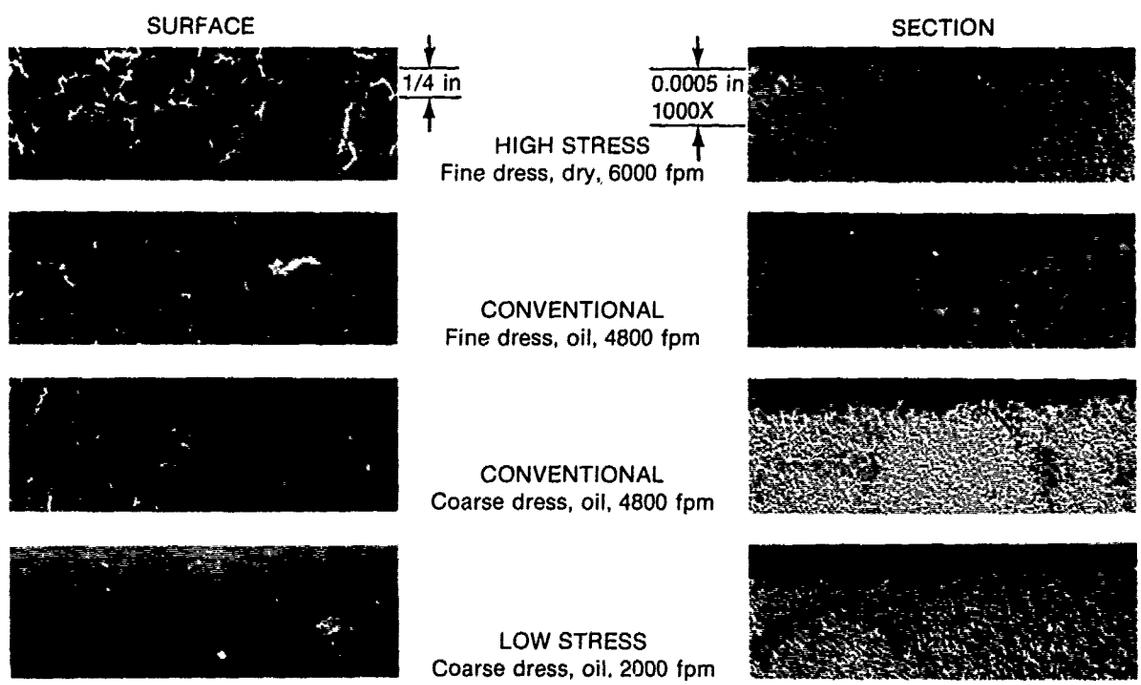


Figure 18.3-64 Effect of different grinding intensities. *Left*, ultraviolet photographs of fluorescent penetrant inspections of the four surfaces of a bar of cast nickel base alloy ground under four different conditions of surface grinding. *Right*, corresponding section photomicrographs at 1000X. These photos reveal the presence of cracks and pull-out. The low-stress-ground surface is free of microcracks. (Surface Integrity Encyclopedia[1])

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TABLE 18.3-11 Surface Integrity Effects Observed in Abrasive Material Removal Processes

PROPERTY AND TYPE OF EFFECT	FINISHING, "GENTLE" OR LOW STRESS CONDITIONS	ROUGHING, "OFF-STANDARD" OR ABUSIVE CONDITIONS
Surface roughness:	μin R_a	μin R_a
Average range	4 to 63	32 to 150
Less frequent range	1 to 125	8 to 250
Mechanical altered material zones:	inch*	inch*
Plastic deformation (PD)	0.0003	0.0035
Plastically deformed debris (PD^2)	0.0005	0.0013
Hardness alteration†	0.0015	0.0100
Microcracks or Macrocracks	0.0005	0.0090
Residual stress‡	0.0005	0.0125
Metallurgical altered material zones:	inch*	inch*
Recrystallization	0.0005	—
Intergranular attack (IGA)	***	***
Selective etch, pits, protuberances	0.0002	0.0004
Metallurgical transformations	0.0005	0.0060
Heat-affected zone (HAZ) or Recast layer	0.0007	0.0500
High cycle fatigue (HCF).	percent	percent
Variation from "handbook" values at room temperature§	0 to +62	−95 to 0

SOURCE: G. Bellows and J. B. Kohls.[20]

NOTE: A dash (—) in the table indicates no or insufficient data. A triple asterisk (***) in the table indicates no occurrences or not expected.

*Maximum observed depth normal to the surface.

†Depth to point where hardness becomes less than ±2 points R_c (or equivalent) of bulk material hardness (hardness converted from Knoop microhardness measurements).

‡Depth to point where residual stress becomes and remains less than 20 ksi [138 MPa] or 10% of tensile strength, whichever is greater.

§Handbook values from HCF testing frequently are generated from specimens that have been processed using low stress grinding, hand or gentle machine polishing or occasionally electropolishing. For this table, "handbook" values represent HCF strength values generated from low-stress-ground specimens (with their minor amount of retained but enhancing compressive residual stress). The values are the 10^7 cycle strengths from full-reverse bending tests at room temperature.

TABLE 18.3-12 Low Stress Grinding Procedures

GRINDING PARAMETERS	STEELS AND NICKEL BASE HIGH TEMPERATURE ALLOYS		TITANIUM	
	English	Metric	English	Metric
SURFACE GRIN' ··G				
Wheel	A46HV	[illegible]	C60HV	[illegible]
Wheel speed	2500 to 3000 fpm*	[illegible]	2000 to 3000 fpm*	[illegible]
Downfeed per pass	0.0002 to 0.0005 inch†	[illegible]	0.0002 to 0 0005 inch†	[illegible]
Table speed	40 to 100 fpm‡	[illegible]	40 to 100 fpm‡	[illegible]
Crossfeed per pass	0 040 to 0 050 inch	[illegible]	0.040 to 0.050 inch	[illegible]
Grinding fluid	Highly sulfurized oil	[illegible]	See section 16.3, Codes 81 and 83	[illegible]
TRAVERSE CYLINDRICAL GRINDING				
Wheel	A60IV	[illegible]	C60HV	[illegible]
Whe·· speed	2500 to 3000 fpm*	[illegible]	2000 to 3000 fpm*	[illegible]
Infeed per pass	0.0002 to 0.0005 inch†	[illegible]	0.0002 to 0.0005 inch†	[illegible]
Work speed	70 to 100 fpm‡	[illegible]	70 to 100 fpm‡	[illegible]
Grinding fluid	Highly sulfurized oil	[illegible]	See section 16.3, Codes 81 and 83	[illegible]

NOTE: For a wide variety of metals (including high strength steels, high temperature alloys, titanium and refractory alloys), low stress grinding practices develop very low residual tensile stresses. In some materials the residual stress produced near the surface is actually in compression instead of tension.

*Low stress grinding requires wheel speeds lower than the conventional 6000 feet per minute [30 meters per second]. In order to apply low stress grinding, it would be preferable to have a variable speed grinder. Since most grinding machines do not have wheel speed control, it is necessary to add a variable speed drive or make pulley modifications

†Downfeeds or infeeds in the range of 0 0002 to 0.0005 inch per pass [0 005 to 0.013 mm/pass] have been found satisfactory for steels, nickel base high temperature alloys, and titanium alloys. A typical feed schedule calls for removing the last 0.010 inch [0.254 mm] of stock as follows. remove 0.008 inch [0 2 mm] at 0.0005 inch per pass [0 013 mm/pass] and remove the last 0.002 inch [0 05 mm] at 0 0002 inch per pass [0.005 mm/pass].

‡Increased work speeds even above those indicated are considered to be advantageous toward improving surface integrity.

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TABLE 18.3-13 Process Parameter Guidelines for Low Stress Grinding Results

PROCESS PARAMETERS	GUIDELINES
1 Grinding wheel dressing technique	Frequent and coarse to maintain sharpness Maintain sharpness of dressing tool. Avoid dwell in using crush, roll, or single-point dressing tools.
2. Wheel speed	Low, under 3,500 fpm [18 m/s].
3. Downfeed (or infeed) rate	0.0002 to 0.0005 inch/pass [0.005 to 0.013 mm/pass] with programmed reduction from conventional rates.
4. Grinding fluid	Oil-base fluid is preferred.
5. Wheel classification	Soft grade (G, H or I*). Open structure (6 or more). Grain size (60 or coarser).
6. Table (workpiece) speed	High, 50 fpm [15 m/min] and up Crossfeed is preferred to plunge motion.
7. Grinding fluid flow control	Adequate to high fluid flow. Assure placement of fluid between wheel and workpiece. Flow controlling nozzle design. Reduce air film on wheel.

SOURCE: G. Bellows.[13]

NOTE: Process parameter guidelines are listed in descending order of significance to low residual stress generation in the workpiece surface. A machine and setup with good rigidity, freedom from vibration or chatter and well maintained with fine cleanliness are also an aid to grinding performance

*Cylindrical grinding frequently requires use of harder wheels (with J grade prevalent); however, the other parameters must be selected to compensate for this extra hardness.

TABLE 18.3-14 Typical Infeed Schedule for Attaining Low Stress Surfaces by Grinding

STEP	WORKPIECE STOCK REMOVAL*	INFEED RATE inch/pass
Rough Grinding	From raw material dimension to within 0.010 inch [0.25 mm] of desired final dimension	up to 0.002†
Dress wheel		
Semi-finish Grinding	From 0.010 inch [0.25 mm] to 0.001 inch [0.025 mm] of final size	0.0003 to 0.0006
Dress wheel	Optional	
Finish Grinding (to low stress levels)	From 0.001 inch [0.025 mm] to final size	0.0001 to 0.0002
	Optional: at final size, with continued application of grinding fluid	2 to 4 spark-out passes

SOURCE: G. Bellows.[13]

*Data applies to the radius for cylindrical grinding and to the depth for surface grinding.

†This roughing rate should be such that roughness, tears, cracks, or microcracks in the surface are of lesser magnitude than the material remaining to be removed by the finishing and semi-finishing cuts.

TABLE 18.3-15 Influence of LSG Parameters on Production Rates

RANKING IN INFLUENCE ON RESIDUAL STRESS	DIRECT INFLUENCE ON MATERIAL REMOVAL RATE AND PRODUCTION TIME	MINOR INFLUENCE ON PRODUCTIVITY	NO INFLUENCE ON PRODUCTION RATE
1 (most) 2 3	Infeed rate	Dressing	Wheel speed*
4 5 6	Table speed	Wheel grade	Lubricant
7 8 9 (least)			Machine type and quality Rigidity of setup Coolant nozzle design

SOURCE: G Bellows.[13]

NOTE: It is possible to achieve the "best of both worlds"—high surface integrity *and* good productivity—if a careful selection among the LSG parameters is made.

*At very low sheel speeds, a wheel acts like a softer wheel and needs more frequent dressing and thereby has a minor influence or production rates.

TABLE 18.3-16 Low Stress Grinding Troubleshooter Checklist

1. Check that **planned machine settings** are being used.
2. Is **wheel grade** correct?
3. Check for correctness and freshness of wheel **dressing.**
4. Check for changes in **workpiece material** or its metallurgical state.
5. Are set values of **feed and speed** being attained and is **infeed program** of reductions being followed?
6. Is **grinding fluid** correct, clean and inserted properly?
7. Check fixtures and machine rigidity.
8. Is workpiece clean and initially free from cracks?
9. Check inspection techniques

SOURCE G. Bellows [13]

TABLE 18.3-17 Grinding Parameters for IN-100 Turbine Blades (Case A resulted in cracks; Case B resulted in no cracks)

GRINDING PARAMETERS	CASE A (Cracks)	CASE B (No Cracks)
Wheel	38A10018VBE	38A8018VBE
Wheel speed	5,500 fpm	2,800 fpm
Table speed	20 fpm	20 fpm
Infeed per pass	0.004 inch	0.002 inch
Fluid	Sulfo-chlorinated oil	Highly sulfurized oil
Grinding cycle	Rough: 0.060 inch at 0.004 inch/pass, dress. Leave 0.100 inch/side for finish operation. Finish: 0.012 inch from finish size (3 passes at 0.004 inch/pass; 2 sparkout passes).	Dress: feed 0.060 inch at 0.002 inch/pass; Dress: feed 0.060 inch at 0.002 inch/pass; Dress: feed 0.010 inch at 0.002 inch/pass to finish size.

18.3 Surface Integrity

TABLE 18.3-18 Fatigue Strength Variation from Different Grinding Conditions

MATERIAL	FATIGUE STRENGTH*					
	Gentle or Low Stress Grinding		Conventional Grinding		Abusive Grinding	
	ksi	MPa	ksi	MPa	ksi	MPa
High Strength Steels:						
4340 (Q & T, 50 R_c)	102	703	70	483	62	427
4340 Mod (Q & T, 53 R_c)	122	841	65	448	62	427
Maraging steel, 300 Grade (STA, 54 R_c)	105	724	82	565	85	586
High Temperature Nickel Base Alloys:						
Inconel Alloy 718 (STA, 44 R_c)	60	414	24	165	–	–
AF 95 (STA, 50 R_c)	75	517	24	165	26	179
AF2-1DA (STA, 46 R_c)	70	483	25	172	20	138
Rene 80 (STA, 40 R_c)	42	290	18	124	16	110
Titanium Alloys:						
Ti-6Al-4V (Beta rolled, 32 R_c)	62	427	–	–	13	90
Ti-6Al-6V-2Sn (STA, 42 R_c)	65	448	30	207	20	138
Ti-6Al-2Sn-4Zr-2Mo (STA, 36 R_c)	68	469	17	117	10	69

*Room temperature, 10^7 cycles full-reverse bending

TABLE 18.3-19 Low Cycle Fatigue Test Data From Surface-Ground Materials

MATERIAL	GRINDING CONDITION	STRESS FOR FAILURE AT 20,000 CYCLES*	
		ksi	MPa
4340 (Q & T, 50 R_c)	Gentle surface grind	165	1,138
	Abusive surface grind	142	979
Ti-6Al-4V (Beta rolled, 32 R_c)	Gentle surface grind	92	634
	Abusive surface grind	71	490
Inconel alloy 718 (STA, 44 R_c)	Gentle surface grind	160	1,103
	Abusive surface grind	127	876
Rene 80 (STA, 40 R_c)	Gentle surface grind	55	379
	Abusive surface grind	45	310

*At room temperature.

Specific Guidelines and Data for ELECTRICAL Material Removal Processes

The molecule by molecule dissolution of the electrically conductive workpiece in electrochemical machining (ECM) is a forceless material removal that introduces no residual stresses into the workpiece. The surface texture is smooth, has no lay pattern, and can approach a metallograph-polish caliber even to revealing individual grain patterns. The absence of beneficial residual stress and/or cold working in the surface frequently results in high cycle fatigue strengths less than that produced with conventionally prepared surfaces. If needed, the addition of a post-ECM process such as shot peening or rolling can add a beneficial compressive residual stress. Some slight softening of the surface has been observed in some alloy-electrolyte combinations. The key to good ECM surfaces is a careful match of the electrolyte composition with the metallurgical state of the workpiece material plus careful control of the operating parameters, especially the current density. Selective etching, intergranular attack (IGA) or pitting may occur in the low current density areas adjacent to the main electrode high current density areas. Static material properties have not been found to be affected by ECM. Hydrogen embrittlement has also not been attributed to ECM (the hydrogen ions form at the cathode and are in the molecular state before reaching the anodic workpiece surface).

The charts and guidelines that follow have baselines the same as those for the mechanical material removal processes. Figures 18.3-65 to 18.3-73 illustrate good or poor surface effects from the electrochemical processes. Microhardness examples are shown in figures 18.3-67, 18.3-71 and 18.3-72, and residual stress patterns are shown in figures 18.3-66 and 18.3-72. High cycle fatigue strength summary data are shown in figure 18.3-74. Table 18.3-20 is a summary of the surface integrity effects observed during the examination of several thousand pieces of data. Other electrical machining illustrations are figures 18.3-5, 18.3-15, and 18.3-17.

Electrical Process Guidelines that Promote Good Surface Integrity Results

1. Surface roughness standards should be reassessed when applying ECM because ECM produces unusual surface textures with no lay pattern.

2. Well controlled ECM does not induce any stresses into the surface.

3. High current densities are desirable in the cutting gap for good finishes and rapid metal removal.

4. The current density in the workpiece should be carefully planned to prevent overheating in the material.

5. Relentless process controls should be supplemented with periodic metallographic checks from representative surfaces.

6. The work material heat treat state should be precisely known and controlled to assure the best repeatability of ECM surfaces.

7. Contact between the electrolyte and workpiece without current flow should be minimized.

8. Localized overheating of the workpiece as a result of poor connections or short circuits should be carefully examined for the extent of any damage. Removal of the surface discoloration is insufficient, as demonstrated in figure 18.3-75.

9. Careful and complete rinsing of the electrolyte from the workpiece is essential. Ultrasonic agitation of the cleaning bath is helpful.

10. Selective etching, excessive roughness, intergranular attack or pitting are evidences of less than optimum operating conditions or tooling practices. These conditions can occur on surfaces subjected to low current density in the presence of the electrolyte or in areas adjacent to the main electrode cutting face.

11. Room temperature fatigue endurance strength is generally lower as compared to that of low stress conventionally ground specimens and represents the unblemished or unaffected material properties state. The lack of any residual stress in electrochemically machined surfaces can account for the differences observed in fatigue strength.

12. The use of a post-ECM shot peening or rolling treatment may be desirable to enhance component fatigue strength.

13. Anomalies in the workpiece surface or microvariations in material composition can influence the surface quality and may be exposed by ECM.

14. Some surface softening will occur in many, but not all, materials.

15. An increase in roughness of the ECM surface can be a significant alert to the departure from optimum or preplanned operating conditions.

16. Hydrogen embrittlement is not attributable to ECM.

Special Comments Concerning Surface Integrity Practices for Electrical Machining Processes

High current densities produce improved finishes and high material removal rates. In sharp contrast to conventional machining, ECM finishes improve with the higher material removal rates that accompany high current densities in the main electrode working gap. Rates of electrode advance of 0.001 to 0.005 inch per second [0.025 to 0.127 mm/s] and current densities of 500 to 1500 amperes per square inch [78 to 232 A/cm^2] are frequent. The upper limit for current densities is usually the internal, resistive heating in the workpiece. Inaccuracies or distorting forces can accompany this internal heating. Poor electrical connections or clamps can produce highly localized hot spots that can involve temperatures to the point that microstructural alteration occurs, as shown in figure 18.3-75.

Surface roughness can be a quality control guideline. The usual fine ECM finish, if tracked or plotted, sequencially and frequently can be a good quality control tech-

nique. A gradually changing roughness usually accompanies a slow change in ECM operating parameters; for example rising sludge content, electrolyte temperature decline, etc. A sudden change in roughness frequently can be traced to a change in the metallurgical state of the workpiece material; for example, a new lot of stock.

Areas of low current density should be suspects for intergranular attack or selective etching. At increasing distances from the principal electrode cutting face, the voltage, current and current density all decline and with them the cutting rates. At specific low values, pitting, intergranular attack, selective etching or anodic films can occur. Insulation of the sides of the electrode can concentrate the electrolytic action. Masks on the workpiece surface are only partially effective in reducing these undesirable effects because a groove of removed material will frequently appear at the edge of such masks. These stray etching areas usually have so little material removal activity that dimensional problems are nonexistent and the cosmetic appearance effects can be confined to the anodic film or "blush" that is readily removed.

Random pitting in workpiece surfaces adjacent to ECM'd areas can result from material anomalies. Occasionally groups or single pits will appear on the workpiece in areas adjacent to the ECM'd area. The pitted areas have been exposed to low current density from free flowing electrolyte or electrified mists. The electrolytic action concentrates in the anomalies in the work material, thus generating a pit or ring- shaped depression (around a less conductive inhomogeneity in the material). Some use has been made of this selective cutting tendency as an inspection aid to assess the surface uniformity of material stock.

Control of the metallurgical state of the work material is needed. The proper selection of electrolyte, current density and the other operating parameters must include consideration of the heat treat or metallurgical state of the material. While electrolytic machining will continue at almost the same rate regardless of the material hardness, the presence or absence of IGA can depend on the heat treat state. Many alloys will be free of IGA when ECM'd in the hardened state; some, however, must be ECM'd in the annealed state to be free of IGA. A simple metallographic section of a test piece or coupon is good quality assurance. For example, the massive IGA shown in figure 18.3-68 disappeared completely when the M252 alloy was electrochemically machined in the annealed state.

Accidental short circuits should be carefully examined for subsurface damage. Modern short circuit protection devices have rapid enough action to protect surfaces from severe damage (and in some cases show only barely detectable pin pricks). Older, slower devices have been known to produce microcracking as deep as 0.10 inch [2.54 mm]. Careful examination, removal of damaged areas or reworking can protect the workpiece surface integrity. Occasionally, overheated areas will show only as a light surface discoloration. While the appearance is easily restored, cases have been recorded of nuggets of metallurgically altered material of considerable extent. Figure 18.3-75 illustrates one such nugget that occurred from overheating a Ti-6Al-4V alloy by concentrating the current flow under a connector as a result of a loose adjacent connector.

ECM produces unblemished surfaces. With the lack of mechanical contact with the workpiece, the gentle molecule-by-molecule dissolution of the material, and the minute surface chemistry effects, ECM produces a nearly unblemished surface. From the standpoint of assessment of the pure, uncontaminated or unaffected material properties, specimens prepared by well controlled ECM are unexcelled. Even polishing with worn crocus cloth can have measurable impact on high cycle fatigue values.

Mechanical material removal action in electrochemical grinding (ECG) should be controlled to minimum values. The abrasive action of the electrically conductive wheel used in ECG is intended for removal of the anodic films formed on workpiece surfaces. It is *not* used for significant material removal. The principal material removal action is still electrolytic. Too heavy abrasive action can result in short circuits, abrasive burns or too much residual stress, as in conventional grinding. Less than 5 percent, and frequently as little as 1 percent, of the material removed comes from the mechanical action. One rule of thumb states that no more than two light scratches from abrasive action should be seen in each square inch of surface. The primary purpose of the abrasive action is to provide a clean nascent surface so that the electrolytic action can proceed at the most rapid pace consistent with overheating the workpiece, wheel or electrolyte. With good electrolyte flow control and good operating parameters, ECG will result in stress free and unexcelled surface integrity, as is demonstrated in figure 18.3-73.

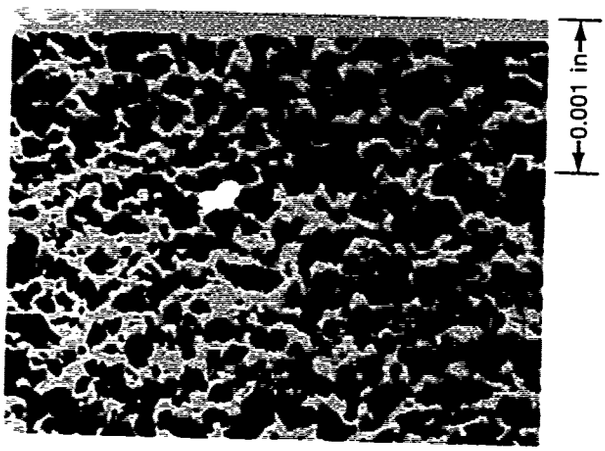


Figure 18.3–65 Typical surface characteristics of 17-4 PH produced by electrochemical machining. *Top*, SEM of surface at 45° and 1000X; *bottom*, section at 1000X. Surface roughness is 29 microinches R_a; R_t = 152 microinches. (Surface Integrity Encyclopedia[1])

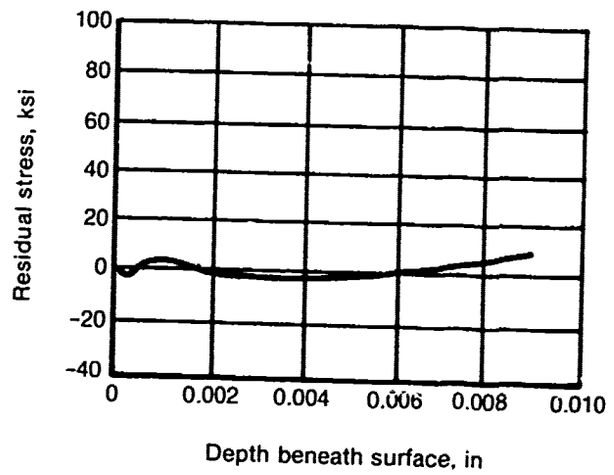
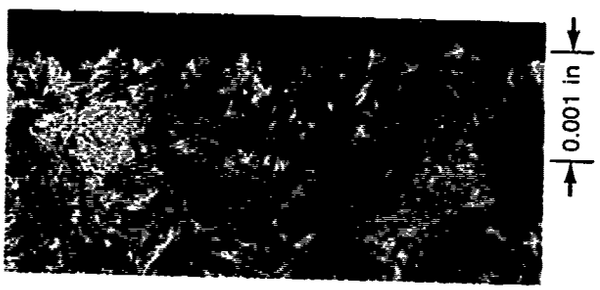


Figure 18.3–66 Typical residual stress profile from ECM (17-4 PH). (G. Bellows and J. B. Kohls[20])



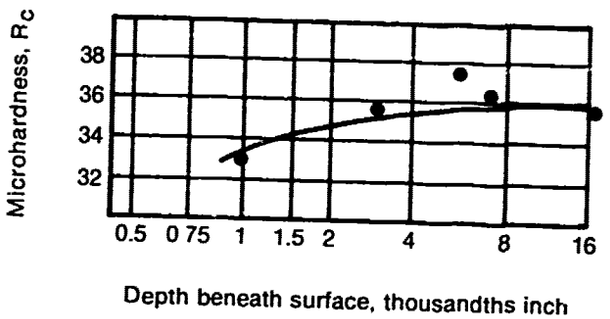


Figure 18.3–67 Typical microhardness traverse from ECM showing surface softening or Rebinder effect (17-4 PH). (G. Bellows and J. B. Kohls[20])

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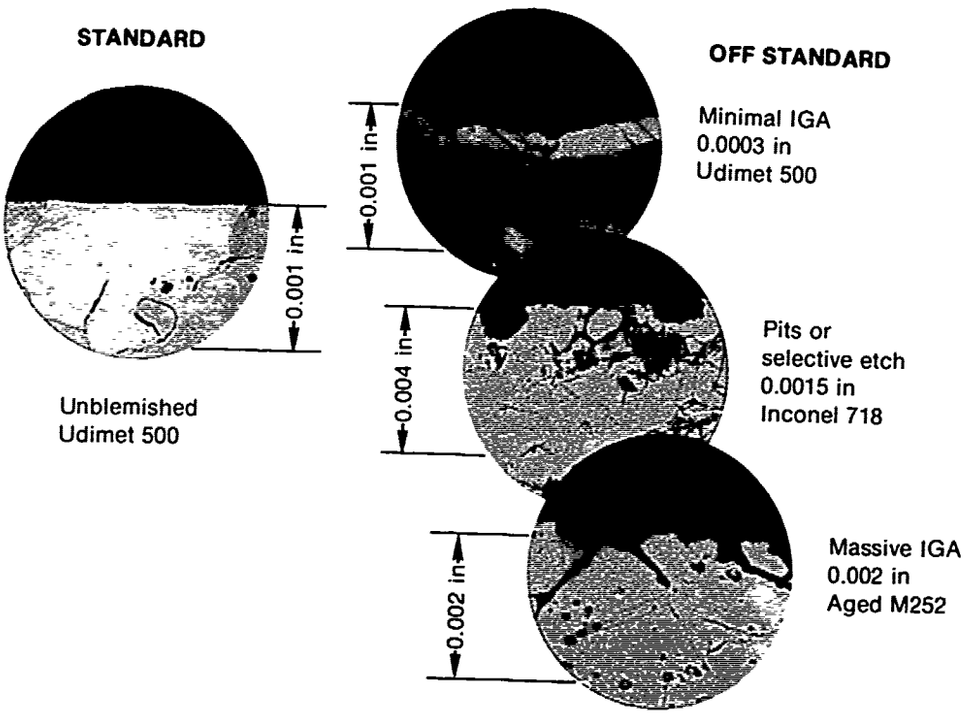


Figure 18.3–68 Comparison of surface sections of "standard" and "off-standard" electrochemical machining of several nickel alloys. (G. Bellows[21])

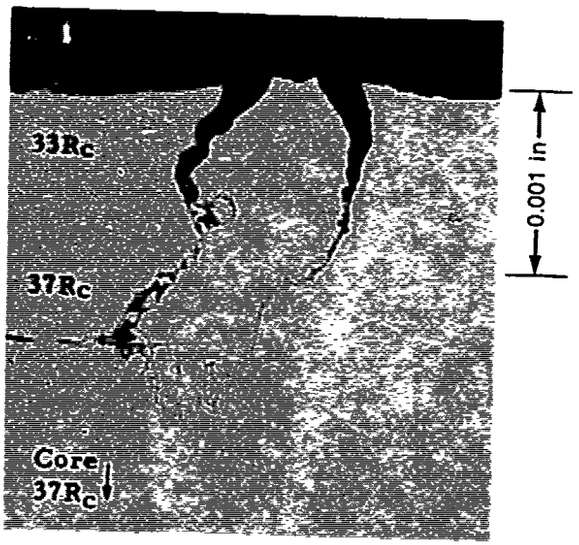


Figure 18.3–69 Electrochemical machining of cast Rene 41 (aged, 47 R_C). Photomicrograph shows a surface having a pronounced tendency toward intergranular attack during an ECM process. Surface alterations, such as shown, are difficult to detect, but they are detrimental and can be avoided through the use of proper process parameters and exacting control of ECM conditions. (W. P. Koster et al[8])

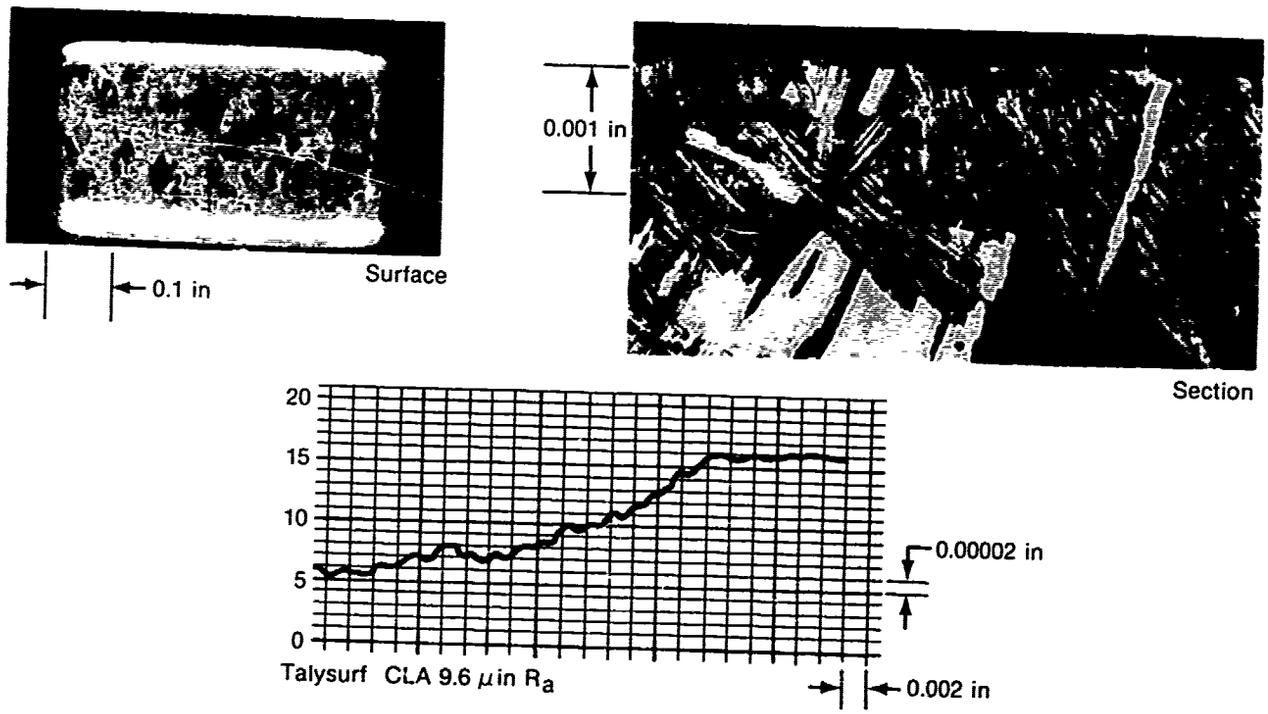


Figure 18.3-70 ECM of Ti-6Al-4V (beta processed). Surface view at 5X, section at 1000X and stylus trace of well performed ECM with NaCl electrolyte. (Surface Integrity Encyclopedia[1])

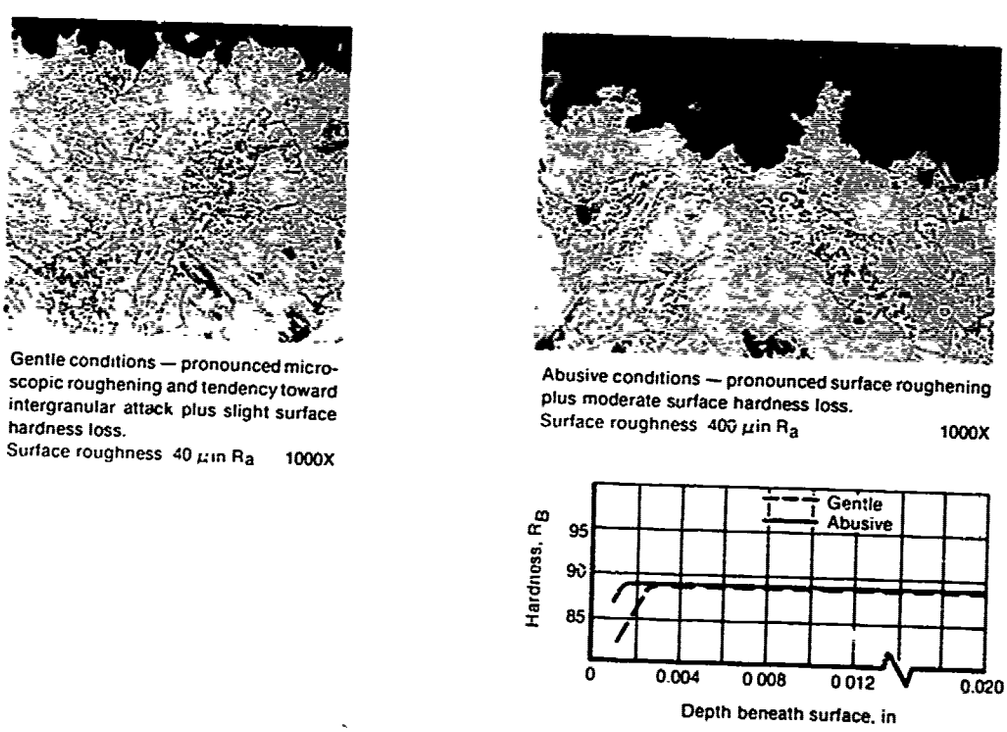
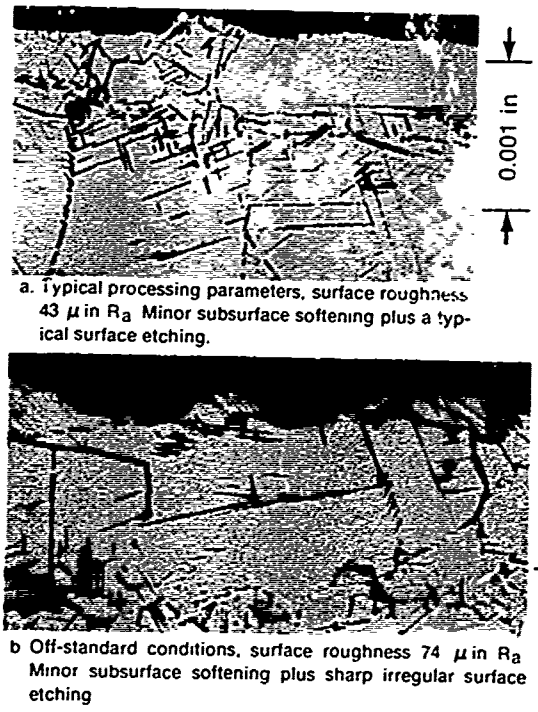


Figure 18.3-71 Surface characteristics of type 410 stainless steel (annealed, 89 R_B) produced by ECM. (W. P. Koster et al[8])

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a. Typical processing parameters, surface roughness 43 μ in R_a Minor subsurface softening plus a typical surface etching.

b Off-standard conditions, surface roughness 74 μ in R_a Minor subsurface softening plus sharp irregular surface etching

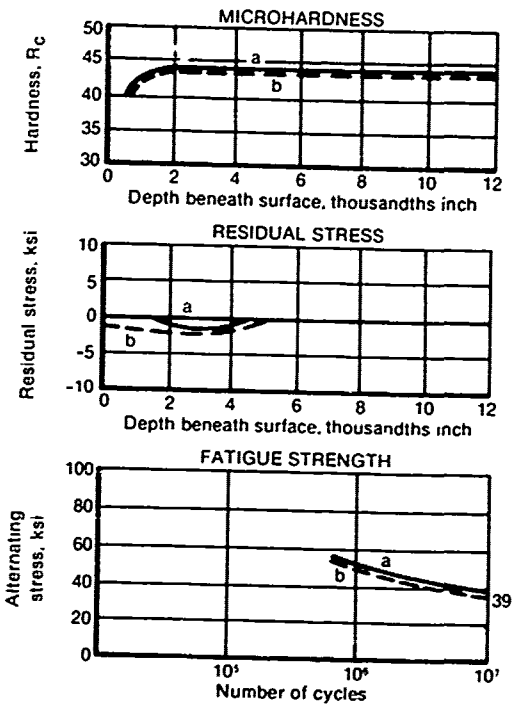
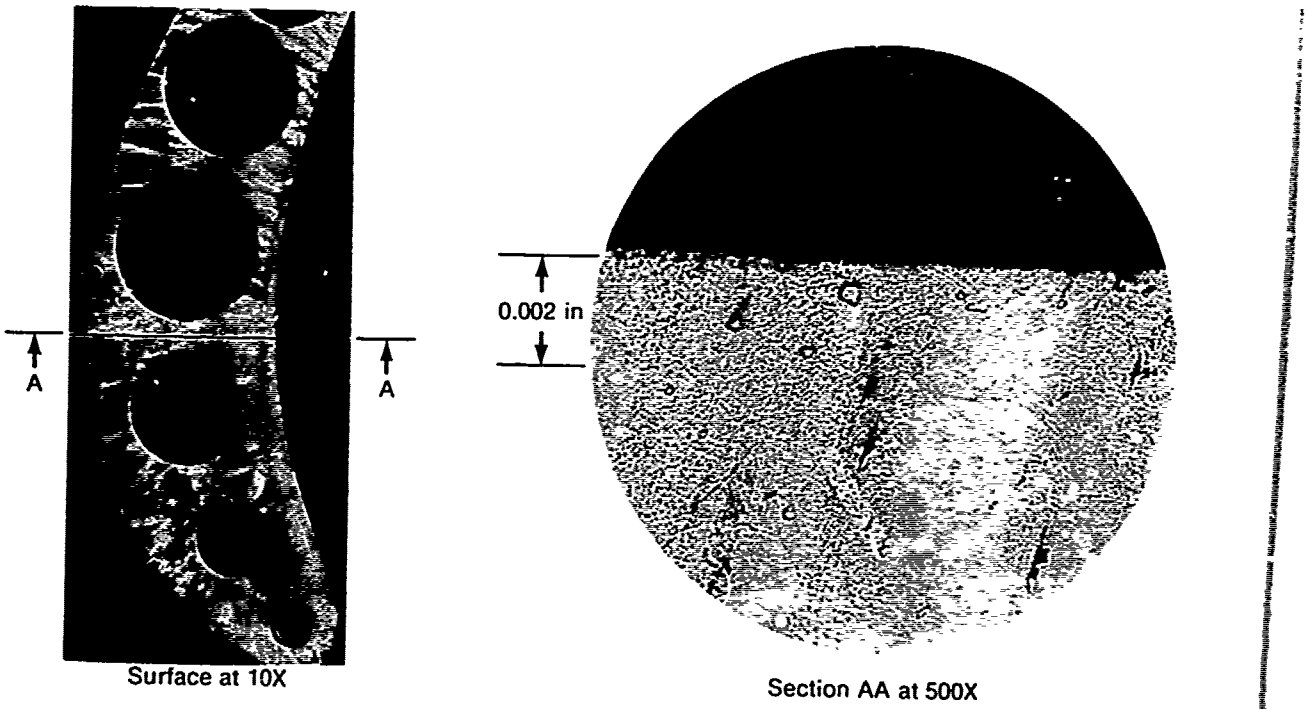


Figure 18.3–72 Standard surface integrity data set for ECM of Inconel Alloy 718 (solution treated and aged, 44 R_C). (Surface Integrity Encyclopedia[1])



Surface at 10X

Section AA at 500X

Figure 18.3–73 Surface characteristics of wrought Udimet 700 turbine airfoil tip produced by ECG. Note the nearly metallographic polish and the absence of scratches in the surface view and unblemished cross section. (Surface Integrity Encyclopedia[1])

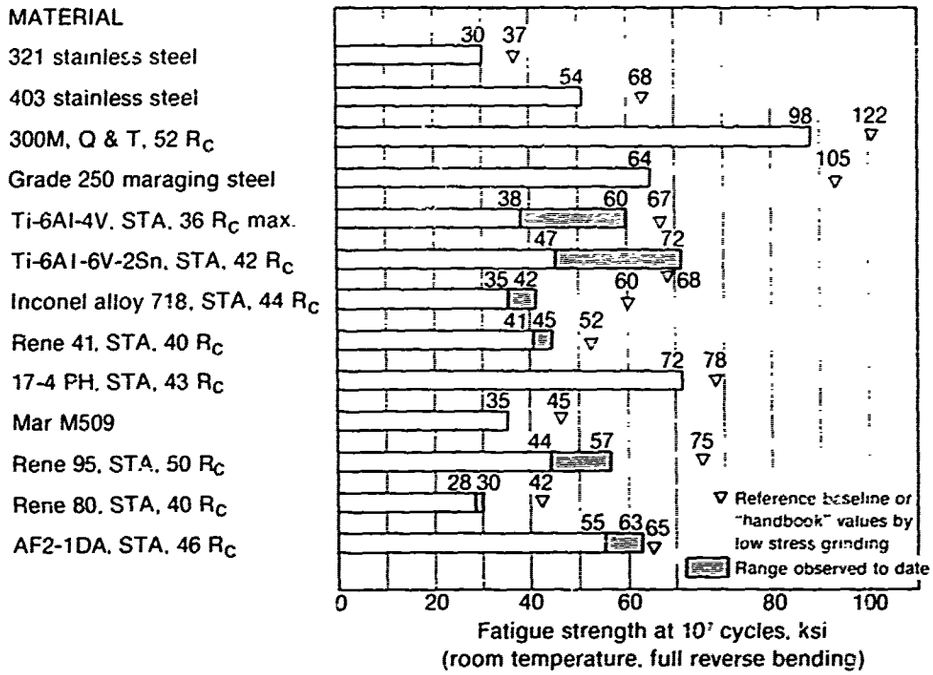


Figure 18.3–74 Summary of high cycle fatigue strengths from electrochemical machining. Note: In the observed ranges, the lower values most generally represent the "off-standard" operating conditions, while the upper values are representative of "standard" or preplanned conditions.

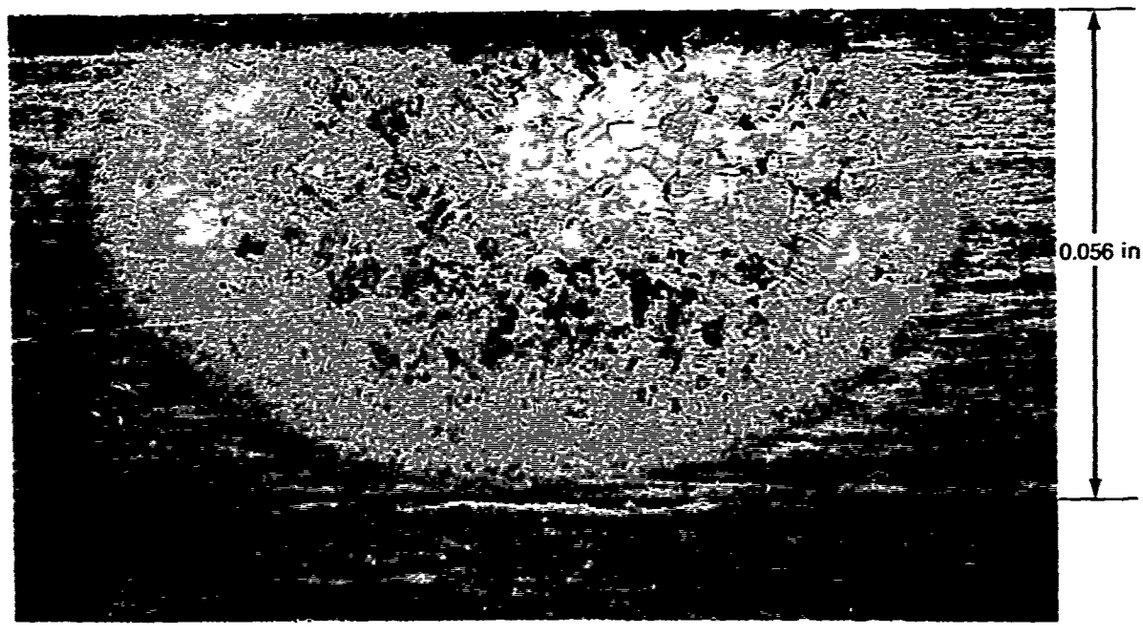


Figure 18.3–75 Metallurgical alteration below the ECM surface of Ti-6Al-4V caused by current concentration under an electrical connection adjacent to a poor (or high resistance) electrical connection, 40X. (G. Bellows[21])

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TABLE 18.3-20 Surface Integrity Effects Observed in Electrical Material Removal Processes

PROPERTY AND TYPE OF EFFECT	FINISHING, "GENTLE" OR LOW STRESS CONDITIONS		ROUGHING, "OFF-STANDARD" OR ABUSIVE CONDITIONS	
Surface roughness:	μin R_a	μm R_a	μin R_a	μm R_a
Average range	8 to 32	0.2 to 0.8	63 to 250	1.6 to 6.3
Less frequent range	2 to 125	0.05 to 3.2	8 to 500	0.2 to 12.7
Mechanical altered material zones:	inch*	mm*	inch*	mm*
Plastic deformation (PD)	—	—	—	—
Plastically deformed debris (PD²)	—	—	—	—
Hardness alteration†	0.0014	0.036	0.0020	0.050
Microcracks or Macrocracks	0.0003	0.008	0.0015 #	0.038
Residual stress‡	0	0	0	0
Metallurgical altered material zones:	inch*	mm*	inch*	mm*
Recrystallization	—	—	—	—
Intergranular attack (IGA)	0.0003	0.008	0.0015	0.038
Selective etch, pits, protuberances	0.0004	0.010	0.0025	0.064
Metallurgical transformations	—	—	—	—
Heat-affected zone (HAZ) or Recast layer	—	—	—	—
High cycle fatigue (HCF)§:	percent		percent	
Variation from "handbook" values at room temperatures§	+6 to −33		−20 to −45	

SOURCE: G. Bellows and J. B Kohls.[6]

NOTE: A dash (—) in the table indicates no or insufficient data.

*Maximum observed depth normal to the surface.

†Depth to point where hardness becomes less than ±2 points R_c (or equivalent) of bulk material has (hardness converted from Knoop microhardness measurements).

‡Depth to point where residual stress becomes and remains less than 20 ksi [138 MPa] or 10% of tensile strength, whichever is greater.

§Handbook values from HCF testing frequently are generated from specimens that have been processed using low stress grinding, hand or gentle machine polishing or occasionally electropolishing. For this table, "handbook" values represent HCF strength values generated from low-stress-ground specimens (with their minor amount of retained but enhancing compressive residual stress). The values are the 10^7 cycle strengths from full-reverse bending tests at room temperature.

Short circuit accidents have caused microcracking as deep as 0.10 inch [0.25 mm].

Specific Guidelines and Data for THERMAL Material Removal Processes

The thermal material removal processes utilize a variety of heat sources to melt, vaporize or sublime the workpiece surface. The rate of material removal is a function of the energy density which can vary from 100 watts per square inch [15 5 w/cm²] with plasma arc or electrical discharge machining (EDM) to 3 x 10^{10} watts per square inch [0.47 x 10^{10} w/cm²] for laser machining. The surface texture reflects the impingement of the heat source and the molten state that occurred, as is shown in figures 18.3-3 and 18.3-76. Surface roughness measurements of reasonable accuracy can be made on these surfaces if stylus traces are averaged over several readings taken in different directions. Roughness increases with increase in process energy level which is directly proportional to the material removal rate, as shown in figure 18.3-77.

The shallow thermal impact of these processes is accompanied by the very rapid quench rate from the heat sink of the bulk of the material. These transient thermal waves produce a recast and/or resolidified layer(s) on the surface with a heat-affected zone (HAZ) below the recast layer(s). Lightly attached splatter and globules appear at higher energy levels. Figure 18.3-78 illustrates most of the effects found. The thickness of the recast layers increases with an increase in the material removal rate, as shown in figure 18.3-79. When EDM is well controlled only a few ten thousandths inch of recast is found, as shown in figure 18.3-80. The recast layer has a heat-affected zone immediately beneath it and of a thickness approximately the same as the maximum recast. Figure 18.3-81 shows typical microhardness traverses with the much harder recast and the usually softened zone below.

Since most of the thermal machining data has been generated using EDM, the temptation to extend these data to other thermal processes should be resisted The significantly different energy rates of laser, for example, produce significantly different effects, as demonstrated in figure 18.3-4. The charts and guidelines that follow have baselines the same as those for the mechanical material removal processes. Figures 18.3-76 to 18.3-92 illustrate good or poor surface effects from thermal material removal processes. Microhardness examples are shown in figures 18.3-81, 18 3-82, 18 3-84, 18.3-86, 18 3-87, and 18.3-89 and typical residual stress patterns in figures 18.3-88 and 18.3-89. A summary of high cycle fatigue strengths from EDM is contained in figure 18.3-94 and table 18 3-22 Table 18 3-21 is a summary of the surface integrity effects observed during the examination of several thousand pieces of data. Other thermal material removal illustrations are figures 18.3-3, 18 3-4, 18.3-11, and 18.3-15.

Thermal Process Guidelines that Promote Good Surface Integrity Results

1. The surface texture is composed of a random array of overlapping craters or cusps, sometimes with macrocracks at the roughing level of processing, as shown in figures 18.3-3 and 18.3-76.

2. Surface roughness standards should be reassessed when using these processes because they produce unusual surface textures with no lay patterns and require different methods of checking.

3. The prior metallurgical condition of the workpiece is as important to generating surface quality as is the selection of operating parameters.

4. Careful monitoring of the preselected operating parameters is necessary. Some older types of equipment do not maintain their initial settings throughout a long day or run.

5. The depth of the heat-affected zone (HAZ) or recast structure on the surface is approximately proportional to the magnitude of the energy impinging on that surface It is always present to some degree.

6. The HAZ can induce hardness variations and a substantial tensile residual stress in the surface layers.

7. The depth of the HAZ below the recast layers is approximately equal to the depth of the maximum recast. The recast layer in EDM can be controlled precisely and is usually only a few ten-thousandths inch thick.

8. Fatigue strength is frequently severely reduced by the HAZ(s).

9. Highly stressed or critical surfaces should have the HAZ produced by thermal material removal processes removed or modified by a post-processing treatment.

10. Removal of the altered material zones (AMZ) may not be necessary if component or laboratory tests shown that design requirements are being satisfied.

11. Microholes (those less than one millimeter in diameter) produced by thermal processes may not be detrimental to fatigue endurance strength A check by facture mechanics of the critical hole size for a specific material is desirable.

12. On thin components, high current densities may overheat the workpiece.

13. Thorough cleaning to remove dielectric fluids, beads and vapor residue is desirable.

14. The microcracks per inch of cross section can be a valuable clue to the relative thermal sensitivity of materials, table 18.3-23.

Special Comments Concerning Surface Integrity Practices for Thermal Machining Processes

Whenever EDM is used in the manufacture of highly stressed structural parts, the heat affected layer which is produced should be removed or given a remedial post treatment. The altered surface layer(s) which is produced during EDM lowers fatigue strength of alloys significantly. The altered layer consists of a recast layer with or without microcracks, some of which may extend into the base metal, plus metallurgical alterations such as rehardened and tempered layers, heat-affected zones, intergranular precipitates, etc. Concern over the lowered fatigue strength is in reference to highly stressed structures. For many tool and die applications, the altered layer has not caused problems, and there have been reports of improved die life in special applications. Generally, during EDM roughing, the layer showing microstructural changes, including a melted and resolidified layer, is less than 0.005-inch [0.127 mm] deep; while during EDM finishing, it is less than 0.001 inch [0.025 mm].

The detrimental high cycle fatigue effects of the surface alterations caused by EDM are shown in comparison with low stress grinding in table 18.3-22 and figure 18.3-94.

Post treatment to restore fatigue strength is recommended to follow EDM of critical or highly stressed surfaces. Since all alloys examined to date show a significant decline in fatigue strength when their surfaces are produced by EDM, it is necessary to apply a modifying post-EDM process in order to restore the surface integrity. There are several effective processes to accomplish restoration or even enhancement. It is recommended that a special surface integrity evaluation be made for critically loaded surfaces. The evaluation should be made on test workpieces or coupons to which the *full* sequence of operations generating the "as-shipped" surface has been applied. Among the frequently used post-treatment processes are the following:

- removal of layers by low stress grinding
- removal of layers by chemical machining
- addition of a metallurgical type coating
- reheat treatment
- application of shot peening

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See figure 18.3-93 and the Specific Guidelines for Post-Treatment Processes.

The thermal nature of these processes always produces a recast and underlying heat-affected zone (HAZ) on the surface being machined. The intensity of the process energy does affect the amount of recast and microcracking However, the thermal sensitivity or chemical complexity of the alloy can also affect the microcracking propensity. Using a constant EDM energy level, the number of microcracks per inch was measured on several nickel alloys. Table 18.3-23 shows the increasing rate of microcrack appearances as the complexity of the alloy increases. These values are the count found in an examination at 1000X of 2 inches (50 mm) of EDM cut surface.

This same study found no significant surface effects differences between cast and rolled states of Hastelloy Alloy X or Rene 41 when processed using EDM It is probable that the energy density in EDM is such as to overwhelm the differences in the energy state between casting and rolling in these alloys.

The degree of microcracking can be a valuable comparison technique to assess the relative thermal sensitivity of alloys.

Laser beam machining (LBM) develops surfaces showing the effects of melting and vaporization. Applications for LBM are not yet common. Recently, however, LBM with oxygen assist has been investigated for cutting instead of shearing various alloys including titanium. Also, LBM has been used for the production of small holes. Wherever LBM is used in manufacturing highly stressed structural members, it should be remembered that in the application of this method the surface is subjected to melting and vaporization. Indications are that such surfaces should be removed or modified. It becomes difficult, however, to apply secondary processing to parts containing very small diameter holes or narrow slots. As a first step, it is suggested that critical parts made by electron beam machining and laser beam machining be tested to see if surface alterations lower the critical mechanical properties.

The concern for EDM recast should be confined only to critically loaded surfaces. Too frequently the reaction to the microcracking seen in the recast layers from EDM or other thermal machining methods is either to reject the processes or apply a drawing note to finish by mechanical means if such a process is used. This approach is costly, eliminates useful alternatives and ignores the altered material zones from mechanical processing (see milling "recast." figure 18.3-34). A more fruitful approach is to apply surface integrity evaluations *only* to those areas of a workpiece that are fatigue or stress corrosion or critically limited in some manner peculiar to the specific applications. Concentrated effort to improve these areas by the method used for their generation or by the application of post-processing treatments is eminently worthy to produce the best surface and component integrity. It is for these areas that the decision must be made to remove or to modify EDM. For all other less critical or noncritical surfaces, specifications can be relaxed with the potential for considerable cost improvements. These less critical areas are usually several times as extensive as the critical areas.

The recast layer is *not* a crack propogation barrier. Many section photomicrographs will show microcracks only in the recast layer. It is wrong to assume that the sharp metallurgical structural change at the interface between the recast and the base metal will act as a barrier for the propagation of microcracks. The single metallographic section is too small a sample to assure that no microcrack extends deeper than the recast, and no data are available on such microcrack propagation characteristics.

Very minor fatigue strength differences exist between finishing and roughing EDM. Finishing and roughing EDM are characterized by a wide difference in surface roughness levels (50 to 200 microinches R_a [1.25 to 5.0 μm R_a]) and wide differences in recast layer thicknesses (0.0002 to 0.005 inch [0.005 to 0.127 mm]). High cycle fatigue strength, however, is nearly the same for finishing as for roughing EDM, as shown in figures 18.3-93 and 18.3-94. The roughness values are not as significant as it has classically been assumed to be. Not only the recast layer but also the underlying heat affected zone can be detrimental. For critically loaded surfaces, it is desirable to remove the HAZ or to modify the surface preparation or to conduct extensive testing to assess the reliability of the surface generated for particular applications.

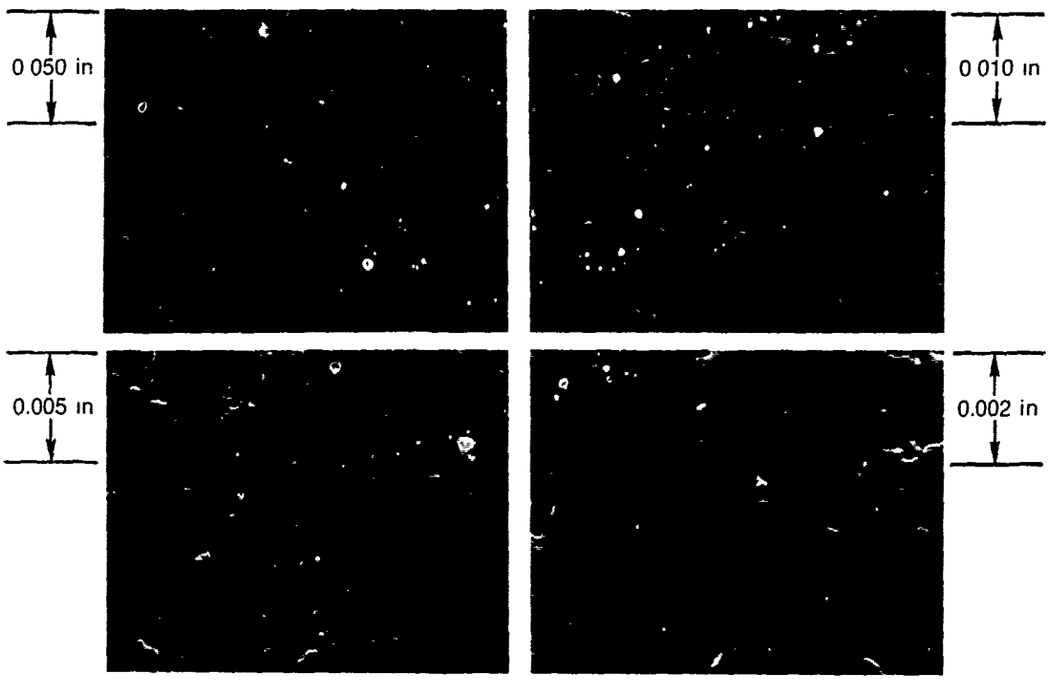


Figure 18.3–76 Scanning electron microscope photomicrographs at successively greater magnifications of finish electrical discharge machining of Inconel Alloy 718 (solution treated and aged). Views taken at 84° to the surface. Surface roughness is 62 microinches R_a. (Surface Integrity Encyclopedia[1])

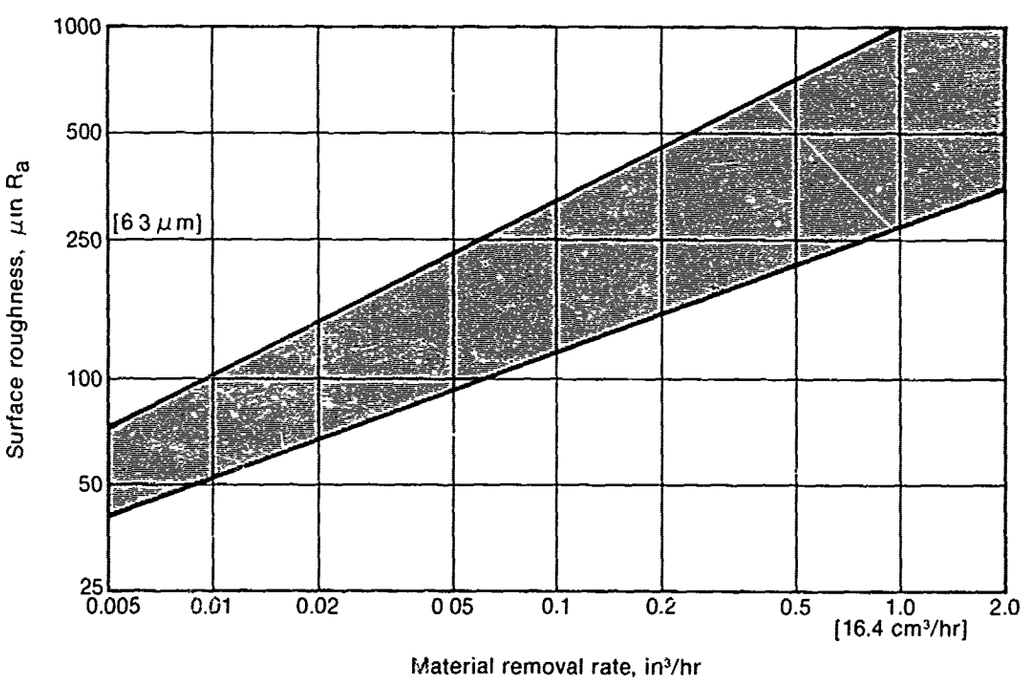


Figure 18.3–77 Approximate relation of surface roughness to material removal rate for electrical discharge machining. (G. Bellows and J. B Kohls[20])

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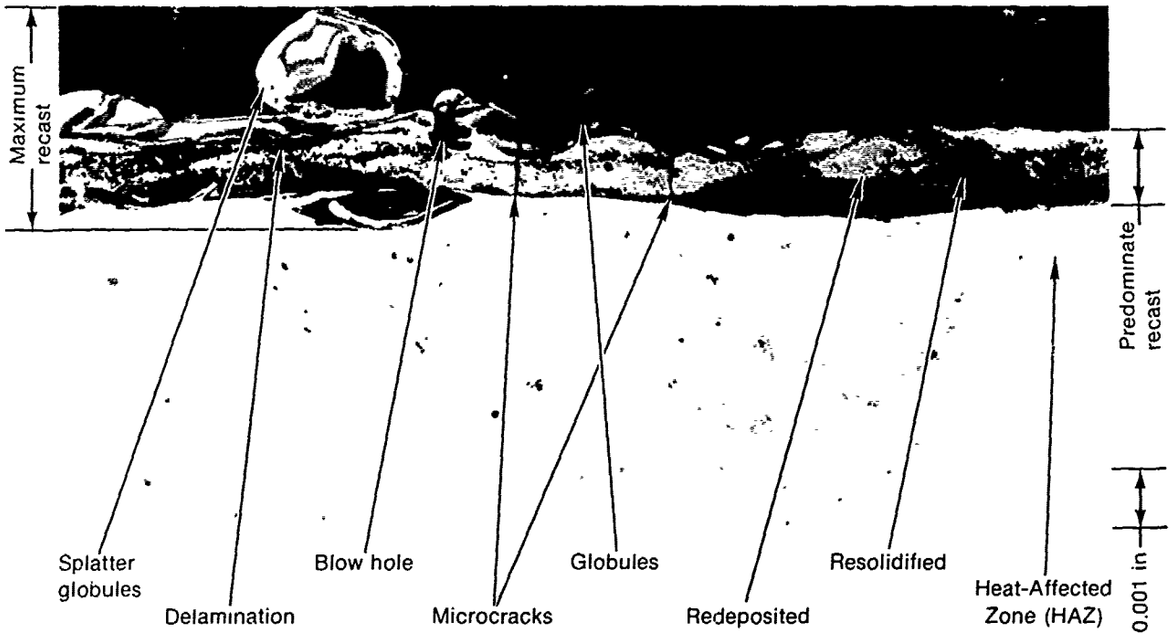


Figure 18.3-78 Recast surface with types of alterations and their descriptors (Hastelloy Alloy X at 300X). (G. Bellows and J B Kohls[20])

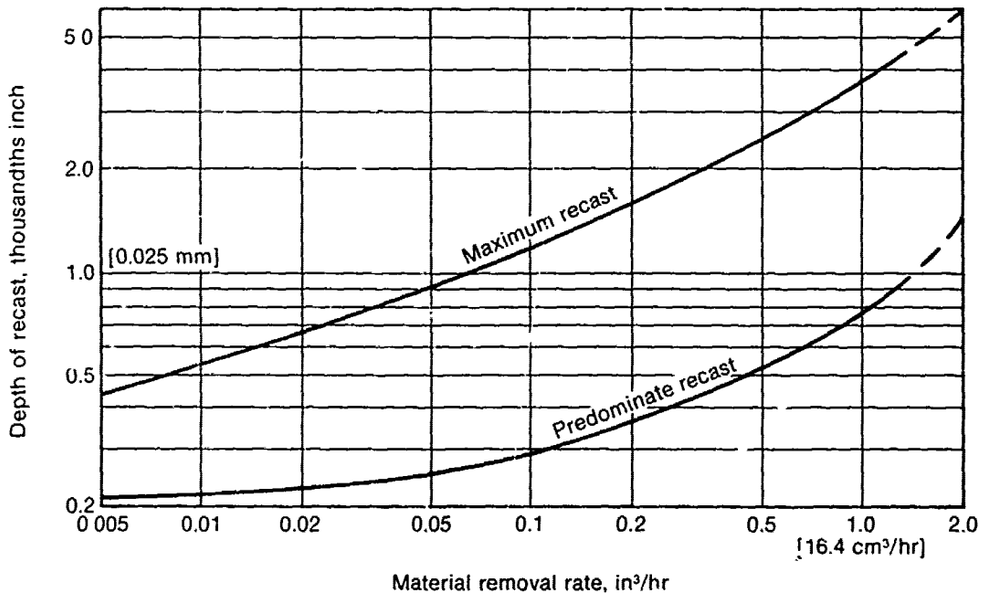


Figure 18.3-79 Depth of recast from electrical discharge machining versus process intensity (material removal rate) for a wide variety of materials. (G. Bellows and J B. Kohls[20])



Figure 18.3–80 Typical well controlled EDM recast and heat-affected zone (0.0002 inch predominant recast from EDM of Udimet 700). (Surface Integrity Encyclopedia[1])

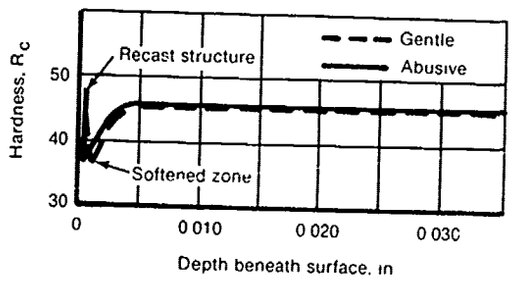
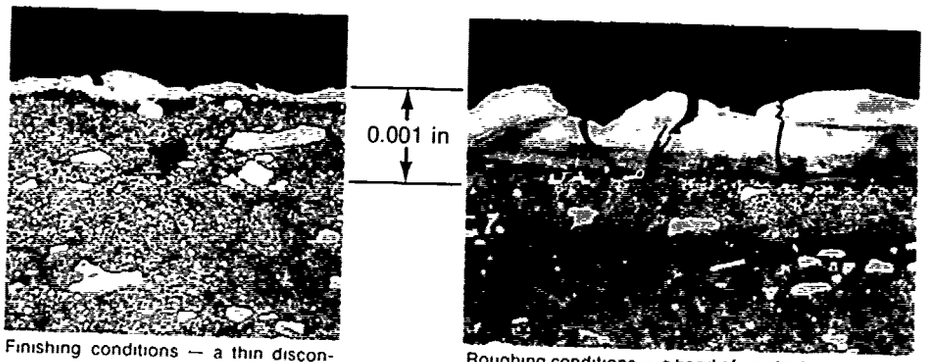


Figure 18.3–81 Typical microhardness traverse on EDM surface of Inconel Alloy 718 (solution treated and aged). (G Bellows and J B Kohls[20])



Finishing conditions — a thin discontinuous recast layer 0 0001 to 0 0002 inch deep was produced on the surface 1000X

Roughing conditions — a band of cracked recast metal and underlying layers of untempered and overtempered martensite were formed The total heat-affected depth was approximately 0 005 inch 1000X

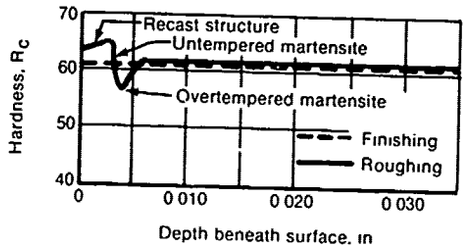


Figure 18.3–82 Surface characteristics of type D2 tool steel (quenched and tempered, 61 R_C) produced by EDM.

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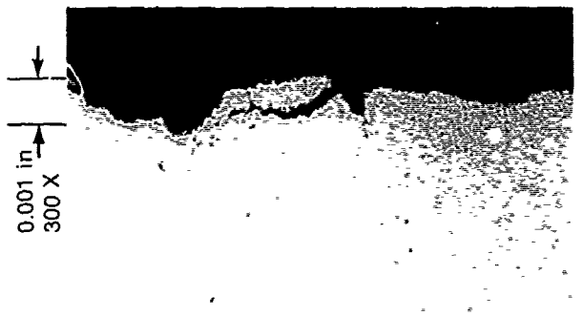
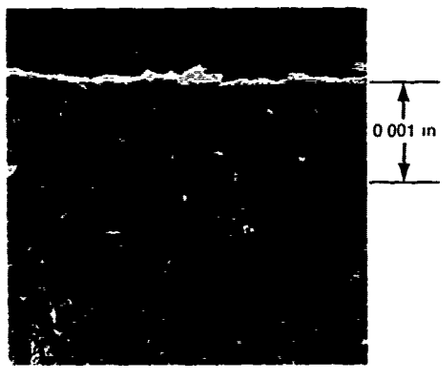


Figure 18.3–83 Surface characteristics of tungsten carbide (883) produced by EDM. (Surface Integrity Encyclopedia[1])



Finishing conditions — discontinuous patches of recast metal plus a thin layer of rehardened martensite (0 0001 inch) are seen No hardness change was detected 1000X



Roughing conditions — globs of recast metal (62 R_C) are spattered on a white layer of rehardened martensite totaling 0 003 inch deep, also at 62 R_C An overtempered zone as soft as 46 R_C is found beneath the surface Total depth of layer affected approaches 0 010 inch 1000X

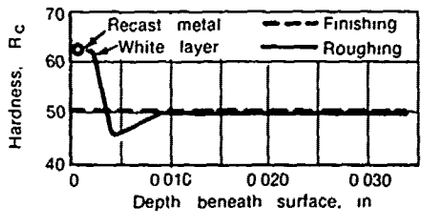


Figure 18.3–84 Surface characteristics of 4340 steel (quenched and tempered, 50 R_C) produced by electrical discharge machining.

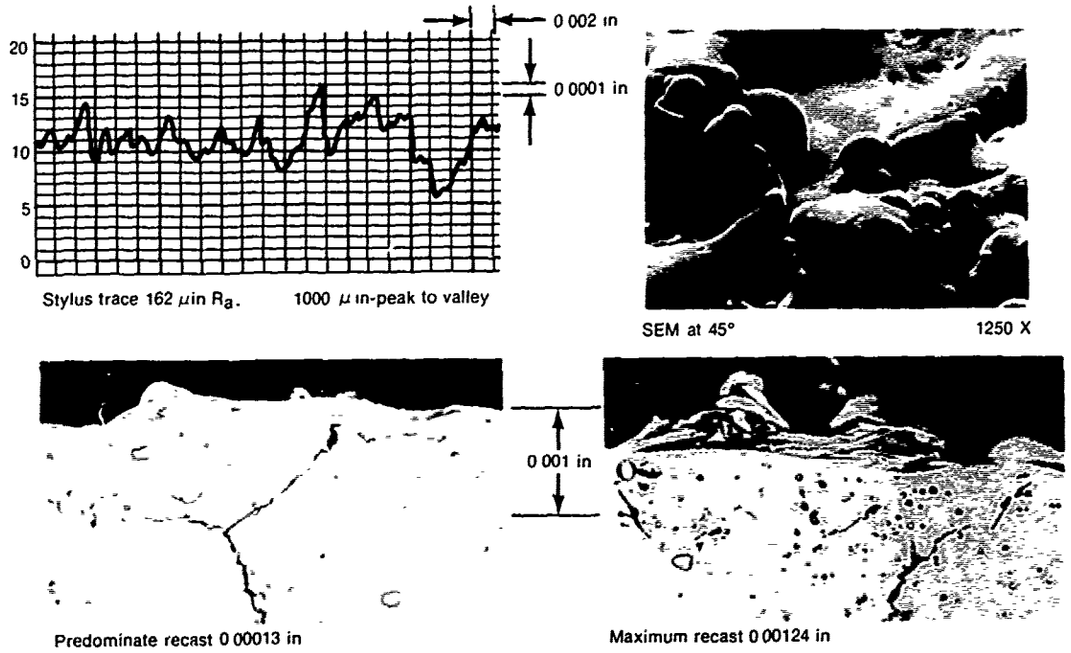


Figure 18.3-85 Typical surface characteristics of rolled Hastelloy Alloy X from "normal" EDM. (Surface Integrity Encyclopedia[1])

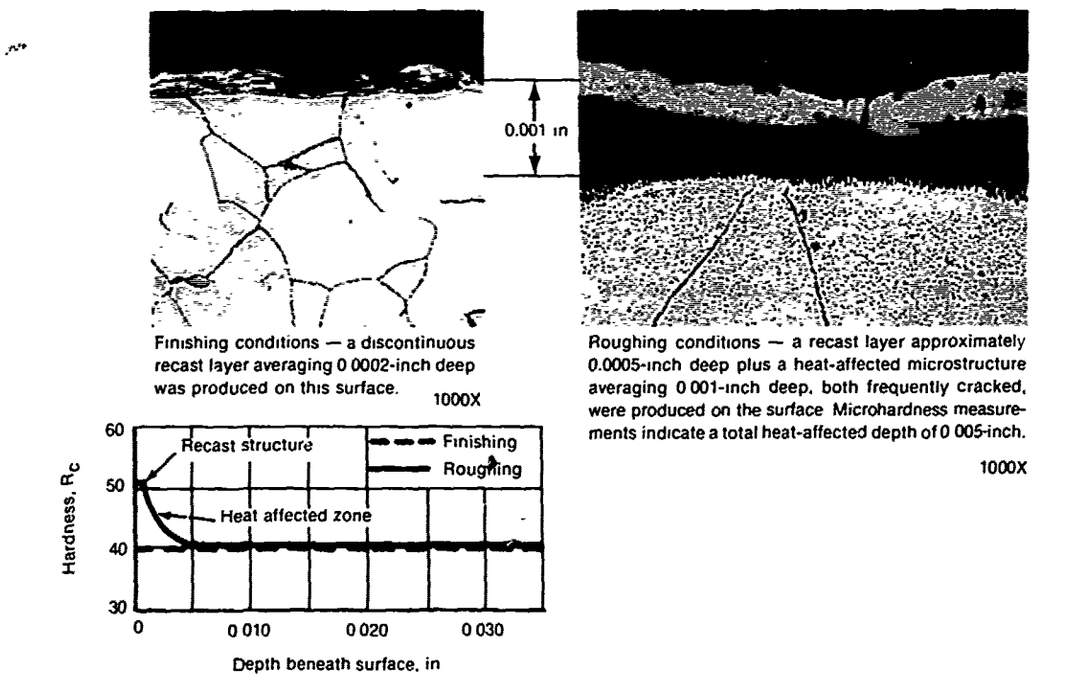
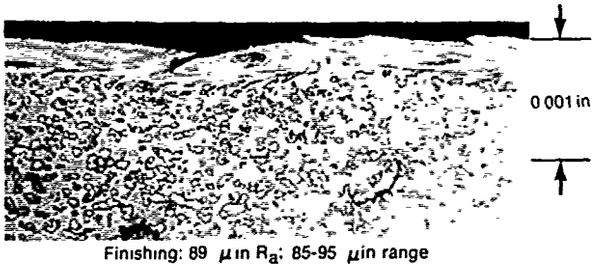


Figure 18.3-86 Surface characteristics of Waspaloy (aged, 40 R_C) produced by EDM. (W. P. Koster et al[8])

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Finishing: 89 μin R_a; 85-95 μin range

Recast 0 0003 inch avg, 0 0005 inch max



Roughing 205 μin R_a. 200-210 μin range

Recast 0 0005 inch avg; 0 0012 inch max.

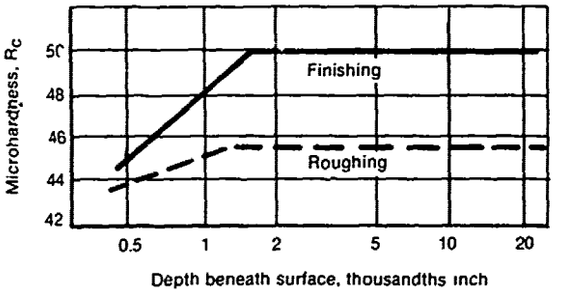


Figure 18.3-87 Surface characteristics of nickel alloy AF2-1DA (solution treated and aged) produced by EDM. (Surface Integrity Encyclopedia[1])

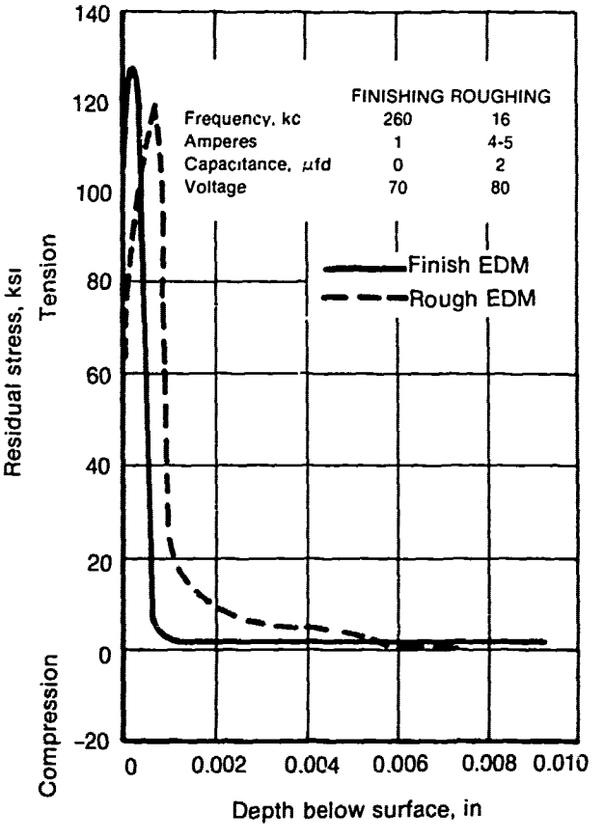
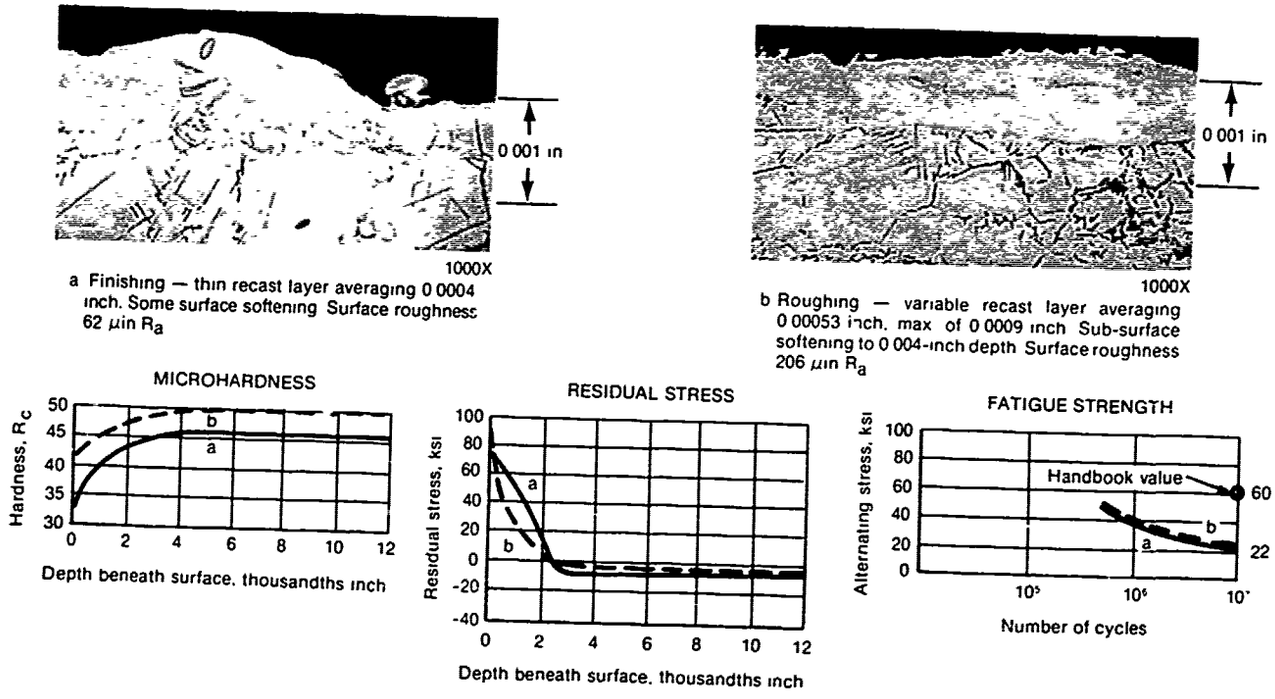


Figure 18.3-88 Residual surface stress profiles in AF 95 (Rene 95) (solution treated and aged, 50 R_C) produced by EDM. See also figure 18.3-93. (W. P. Koster and J. B. Kohls[18])



a Finishing — thin recast layer averaging 0 0004 inch. Some surface softening Surface roughness 62 μin R_a

b Roughing — variable recast layer averaging 0 00053 inch, max of 0 0009 inch Sub-surface softening to 0 004-inch depth Surface roughness 206 μin R_a

Figure 18.3–89 Surface integrity standard data set of EDM of Inconel Alloy 718 (solution treated and aged). Note that thin layers of recast (or the HAZ) can be detrimental to fatigue strength as layers many times as thick. In this alloy, the reduction is 63% from the "handbook" high cycle fatigue strength of 60 ksi. (W. P. Koster et al[9])

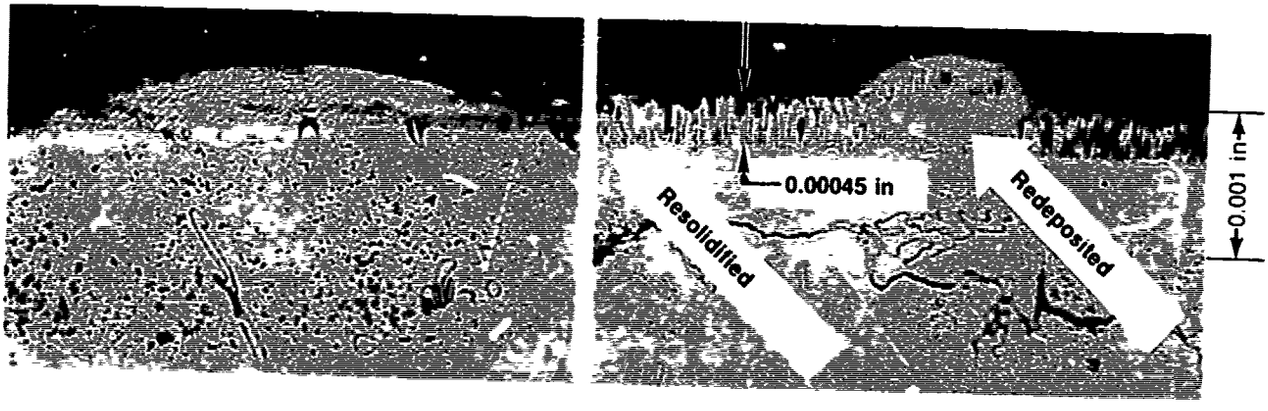


Figure 18.3–90 Typical surface characteristics of hole drilled with laser in cast cobalt alloy X40, 1000X. (Surface Integrity Encyclopedia[1])

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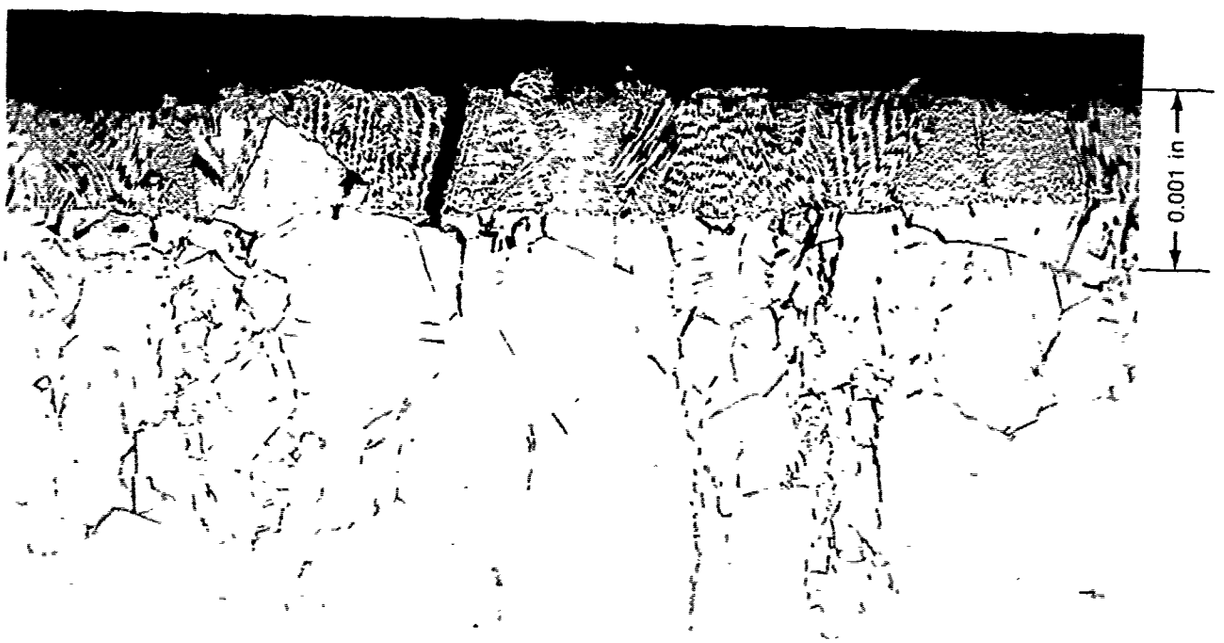


Figure 18.3-91 Surface characteristics of hole in Inconel Alloy 718 produced by LBM showing worst microcrack observed, 0.0008-inch long. Predominant recast 0.0007 inch, maximum recast 0.0029 inch. Note epitaxial growth in deposited layer nucleated on base metal grains. (Surface Integrity Encyclopedia[1])



Figure 18.3-92 Surface characteristics of hole drilled in Rene 80 (solution treated and aged) with ruby laser. Note the two distinct recast layers from vapor deposited during the two laser pulses.

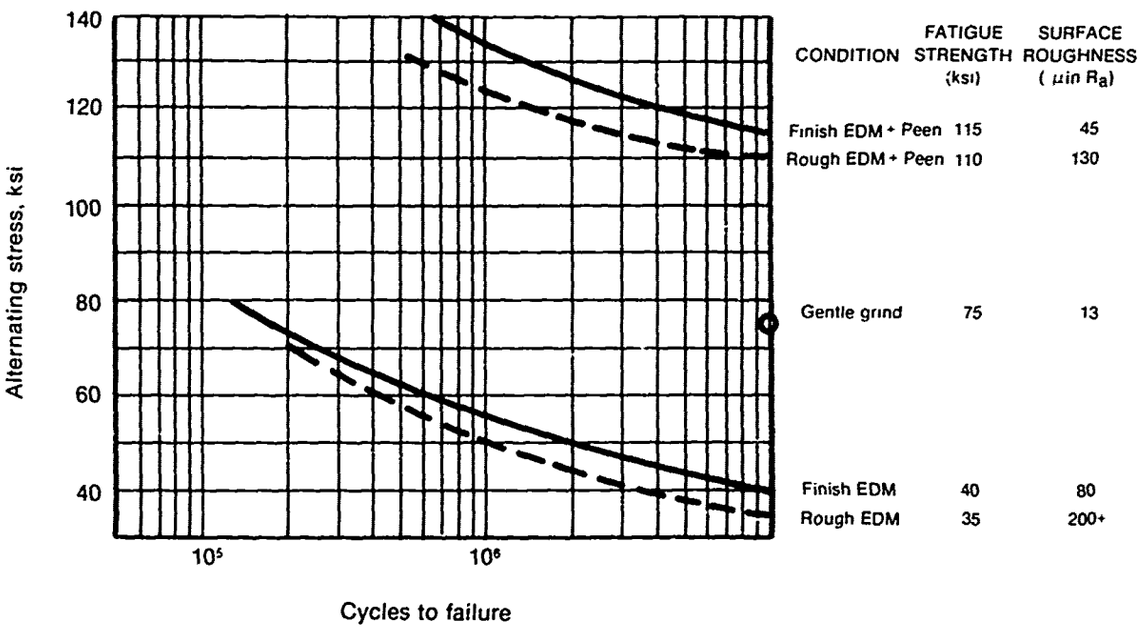


Figure 18.3–93 High cycle fatigue characteristics of AF 95 (Rene 95) (solution treated and aged, 50 R_C) produced by EDM. Mode: cantilever bending, zero mean stress, temperature 75°F. See also figure 18.3–88. Note that finish EDM has about the same reduction in fatigue strength as rough EDM as compared to gentle low stress grinding. Note also the recovery and enhancement of fatigue strength with a post-EDM shot peen treatment. (W. P. Koster and J. B. Kohls[18])

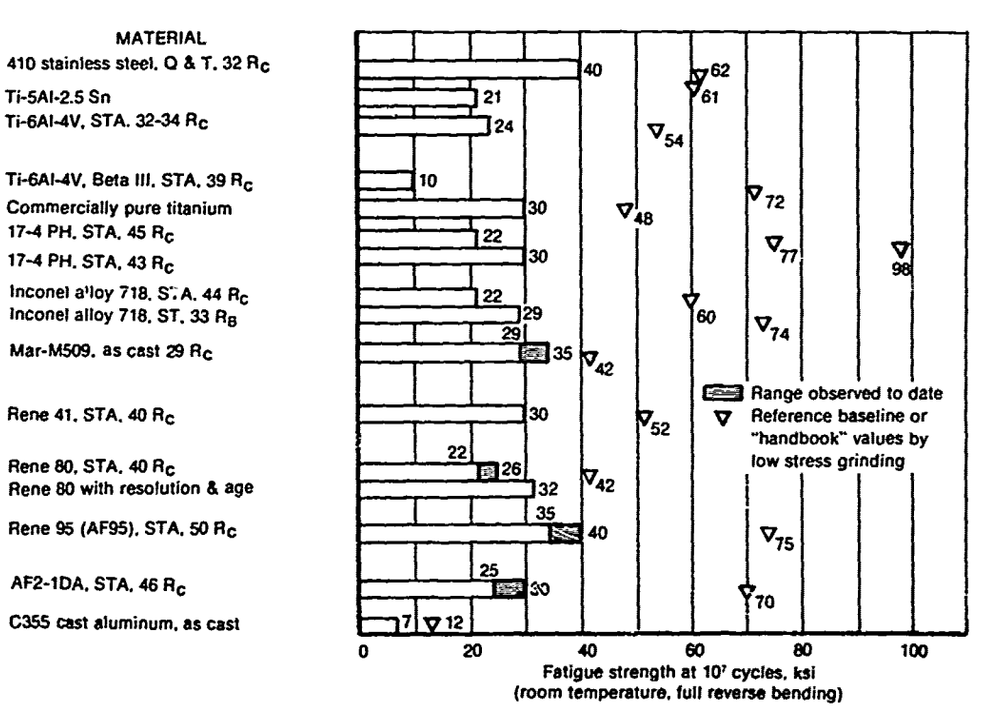


Figure 18.3–94 Summary of high cycle fatigue strength from electrical discharge machining.

18.3 Surface Integrity

TABLE 18.3-21 Surface Integrity Effects Observed in Thermal Material Removal Processes

PROPERTY AND TYPE OF EFFECT	FINISHING, "GENTLE" OR LOW STRESS CONDITIONS	ROUGHING, "OFF-STANDARD" OR ABUSIVE CONDITIONS
Surface roughness:	μin R_a	μin R_a
Average range	32 to 125	125 to 500
Less frequent range	2 to 250	32 to 1,000
Mechanical altered material zones:	inch*	inch*
Plastic deformation (PD)	***	***
Plastically deformed debris (PD²)	***	***
Hardness alteration†	0.0011	0.0080
Microcracks or Macrocracks	0.0003	0.0070
Residual stress‡	0.0020	0.0030
Metallurgical altered material zones:	inch*	inch*
Recrystallization	***	***
Intergranular attack (IGA)	***	***
Selective etch, pits, protuberances	—	—
Metallurgical transformations	—	—
Heat-affected zone (HAZ) or Recast layer	0.0006	0.0050
High cycle fatigue (HCF):	percent	percent
Variation from "handbook" values at room temperature§	—17 to —96	—48 to —64

SOURCE: G. Bellows and J. B. Kohls.[20]

NOTE: A dash (—) in the table indicates no or insufficient data. A triple asterisk (***) in the table indicates no occurrences or not expected.

*Maximum observed depth normal to the surface.

†Depth to point where hardness becomes less than ±2 points R_c (or equivalent) of bulk material has (hardness converted from Knoop microhardness measurements).

‡Depth to point where residual stress becomes and remains less than 20 ksi [138 MPa] or 10% of tensile strength, whichever is greater.

§Handbook values from HCF testing frequently are generated from specimens that have been processed using low stress grinding, hand or gentle machine polishing or occasionally electropolishing. For this table, "handbook" values represent HCF strength values generated from low-stress-ground specimens (with their minor amount of retained but enhancing compressive residual stress). The values are the 10^7 cycle strengths from full-reverse bending tests at room temperature.

TABLE 18.3-22 Fatigue Strength Comparison for Materials Processed Using EDM or Low Stress Grinding

MATERIAL	FATIGUE STRENGTH*	
	Gentle or Low Stress Grinding	EDM (Finishing Conditions)
	ksi	ksi
Inconel 718 (STA, 44 R_c)	60	22
AF 95 (STA, 50 R_c)	75	40
	98†	50†
Rene 80 (STA, 40 R_c)	42	26
AF2-1DA (STA, 46 R_c)	70	30

NOTE: Room temperature unless noted otherwise.

*10^7 cycles full-reverse bending.

†At 1000°F [538°C].

TABLE 18.3-23 Cracking Sensitivity of Nickel Alloys from EDM

MATERIAL	NUMBER OF MICROCRACKS PER INCH [25 mm]*
Hastelloy X (least sensitive)	1.0
Rene 41	1.5
Rene 77	2.5
Rene 80	3.5
Rene 120 (most sensitive)	4.6

SOURCE: G. Bellows.[20]

*Number of microcracks observed in two inches [50 millimeters] of cross section after the specimen was electrical discharge machined at a normal level equivalent to a material removal rate of 0.18 to 0.27 in^3/hour. Observations were made at a magnification of 1000X.

Specific Guidelines and Data for CHEMICAL Material Removal Processes

The chemical family of material removal processes is characterized by an absence of stress introduced into the workpiece as a result of the process. The gentle chemical action of dissolution, molecule-by-molecule or grain-face by grain-face, is typically smooth; however, very smooth surfaces (32 microinches R_a or less [0.8 μm R_a or less]) are slightly roughened, while rough surfaces (125 microinches R_a or more [3.2 μm R_a or more]) are usually smoothed. The uniformity and fineness of the grain structure in the original workpiece is a principal factor in the final roughness. A slight softening of the surface sometimes attributed to the Rebinder effect* is frequently, but not always, found, as demonstrated in figure 18.3-100. Surface discontinuities, such as a weld joint, frequently result in different surface texture and cutting rates.

Achieving good surface integrity from the chemical material removal processes begins with a careful matching of the reagents to the metallurgical state and composition of the work material. Proper process control, particularly the chemical bath "freshness," is essential.

Selective etching, pitting or IGA can occur with improper reagents or overly contaminated or stagnant chemicals. Hydrogen absorption and possible embrittlement can occur with some alloys of steel, titanium or nickel. Post-processing bakes are recommended for this condition.

Static mechanical properties have not been found to be effected by chemical machining (CHM). The absence of beneficial compressive residual stress from chemical machining has the effect of reducing the high cycle fatigue strength when compared to conventionally prepared test specimens.

The charts and guidelines that follow have baselines the same as those for the mechanical material removal processes. Figures 18.3-12 and 18.3-95 through 18.3-100 illustrate some of the good and poor surface effects from chemical material removal processes. A summary of the high cycle fatigue strengths from chemical machining and electropolishing (ELP) is shown in figure 18.3-101. Table 18.3-24 is a summary of the surface integrity effects observed during the examination of several hundred pieces of data.

Chemical Process Guidelines that Promote Good Surface Integrity Results

1. Chemical machining does not induce any significant stress in the machined surfaces.

2. Surface roughness standards should be reassessed when applying CHM because CHM produces surfaces with unusual textures and no lay pattern.

3. The chemical reagents must be matched to the expected metallurgical state of the work material.

4. Surface roughness variations during processing can be a good indicator of changes in the processing conditions, or a change in the metallurgical state of the work material.

5. Careful rinsing of the solutions from the finished workpiece is essential.

6. The control of the metallurgical and heat treat state of the work material is as essential as the control of the process parameters.

7. Selective etching, intergranular attack and pitting can result from off-standard conditions such as high etchant temperatures, incomplete stirring, depleted or unbalanced solutions or contaminated solutions, and variations in the metallurgical state of the work material.

8. Weld areas usually show a different rate of cutting than the base material and an increase in surface roughness.

9. Steel, titanium and nickel base alloys which are susceptible to hydrogen embrittlement should have a post heat treatment of a few hours at a temperature of about 375° to 400°F [191° to 204°C]. Treatment should be applied immediately after chemical processing.

10. Room-temperature, high cycle fatigue strength generally is lower when compared to conventionally prepared, low-stress-ground specimens. This is probably caused by the absence of residual surface stresses.

11. The use of post treatments to add a compressively stressed surface layer may be desirable for enhancing a component's fatigue strength.

12. A test coupon for metallurgical evaluation should be made at least at 90- to 180-day intervals, or whenever the chemical solution is changed.

13. For quality assurance, a deviation of one operating parameter by more than 10 percent from the preplanned value should be cause for alarm and checking. If more than one parameter has deviated by more than 10 percent, the operation should be shut down until corrections have returned the process to a controlled state.

Special Comments Concerning Surface Integrity Practices for Chemical Machining Processes

Special cognizance should be taken of the surface softening that occurs in CHM and ECM of aerospace materials. Microhardness studies on aerospace alloys have shown that chemical machining and electrochemical machining produce a soft layer in a majority of the aerospace alloys.[8] Hardness reductions for chemical machining and electrochemical machining range from 3 to 6 Rockwell C points to a depth of 0.001 inch [0.025 mm] for chemical machining and 0.002 inch [0.050 mm] for electrochemical machining. Shot peening or other suitable post processing should be used on such surfaces to enhance mechanical properties. This surface softening is sometimes labeled the Rebinder effect.

*The Rebinder effect is the modest softening of surface layers of an object upon application of selected chemical solutions that vary with the material of the object.[7]

18.3 Surface Integrity

Surface integrity evaluations should be made when chemical (CHM) and electrochemical (ECM) processes are used for finishing critical parts. The fatigue strength of surfaces produced by controlled chemical and electrochemical processes has often been found to be lower than that produced by some of the more commonly used material removal processes. This is generally attributed to the unworked, stress-free surface produced by processes such as electrochemical machining (ECM), electropolishing (ELP), and chemical machining (CHM). There is evidence that processes such as milling and polishing may sometimes provide beneficial fatigue resistance as a result of cold working or compressive residual stresses; therefore when substituting CHM for other machining processes, it may be necessary to add post-processing operations such as steel shot or glass bead peening or mechanical polishing. Some companies require peening of all chemically or electrochemically machined surfaces of highly stressed structural parts.

Heat treat state is a principal factor in good chemical machining results. The chemical machining of Rene 41, for example, is very sensitive to the heat treat state of the material. Material removal is at the rate of 0.0005 inch per minute [0.0127 mm/min], and the surface roughens slightly when in the full solution-treated state. When aged, however, massive IGA appears. Figure 18.3-99 illustrates the differences. These differences occur with identical processing parameters. The material quenching rate is the principal variable. The best chemical machining of Rene 41 occurs when the material is in a fine-grained structure with the best uniformity. The quick quench in hot rolling, plus the well-worked structure of thin (under 0.100 inch [2.54 mm]) sheet stock yields the best material condition for chemical machining. Increased thickness and slower quench rates tend to produce increased roughness and slower material removal rates. The aged condition usually produces a surface that is rough (150 to 400 microinches R_a [3.75 to 10 μm R_a]) and filled with IGA. In the worst case, a film forms on the surface exposed to the chemicals, inhibiting the action. This film must be mechanically removed before chemical machining can be continued

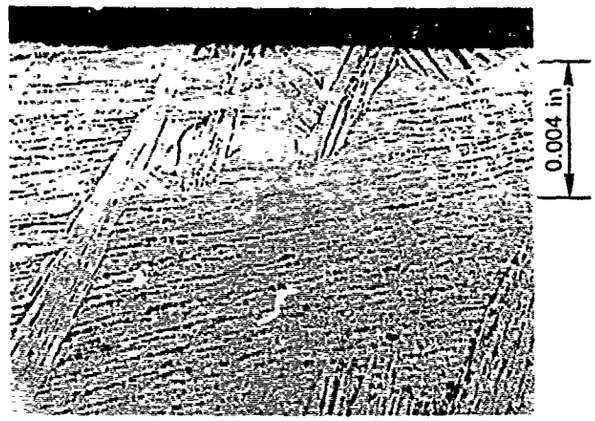


Figure 18.3-95 Unblemished surface section of cast Ti-5Al-2.5Sn (A110 alloy) produced by well controlled chemical machining, 250X. (Surface Integrity Encyclopedia[1])

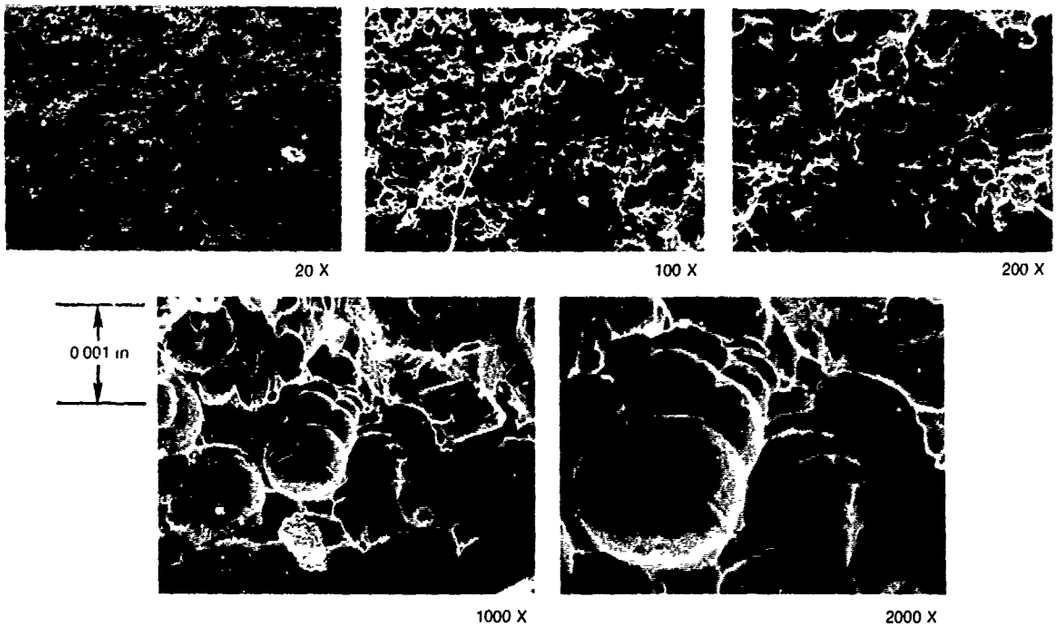
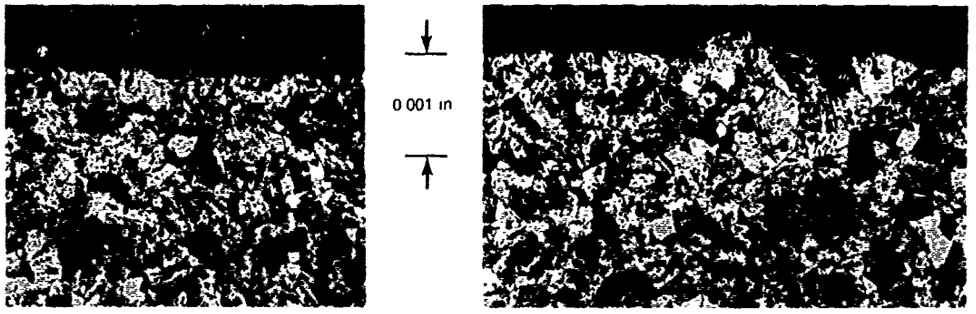


Figure 18.3-96 Surface texture of chemically machined Rene 41. SEM photos at 20, 100, 200, 1000, and 2000X taken at 84° to surface. Surface roughness 500 microinches R_a from off-standard conditions. (G. Bellows[22])



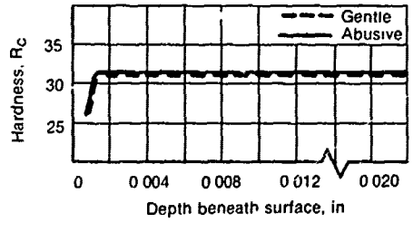


Figure 18.3-97 Surface characteristics of 4340 steel (annealed, 31-36 R_C) produced by CHM.

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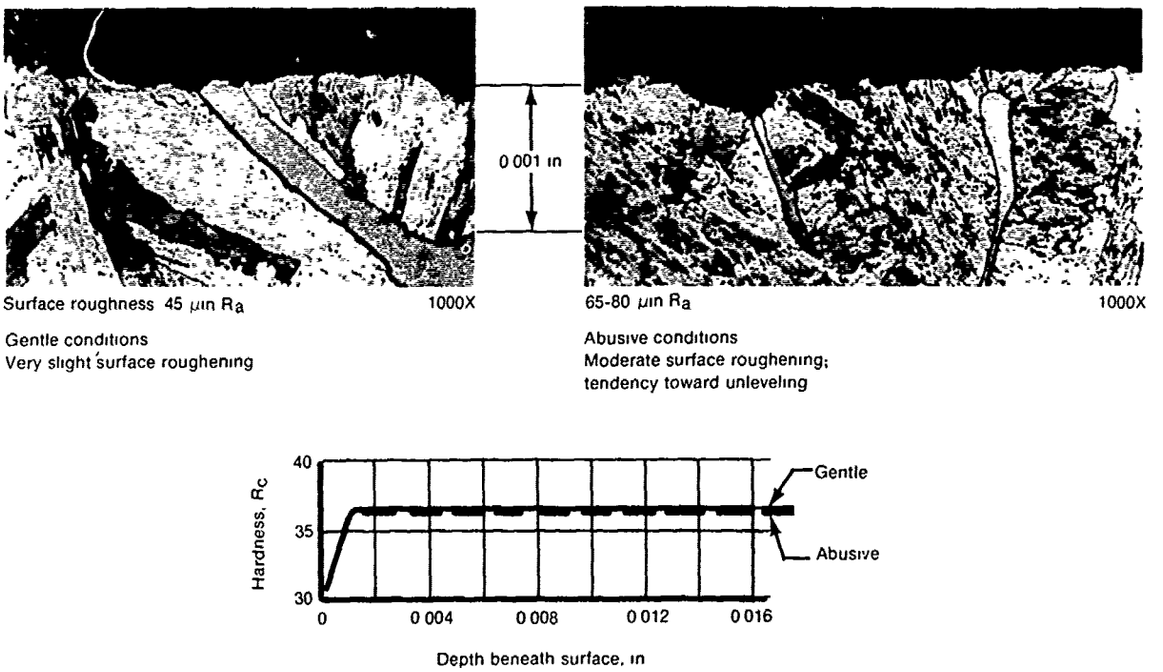


Figure 18.3-98 Surface characteristics of 17-4 PH stainless steel produced by CHM. (W. P Koster et al[8])

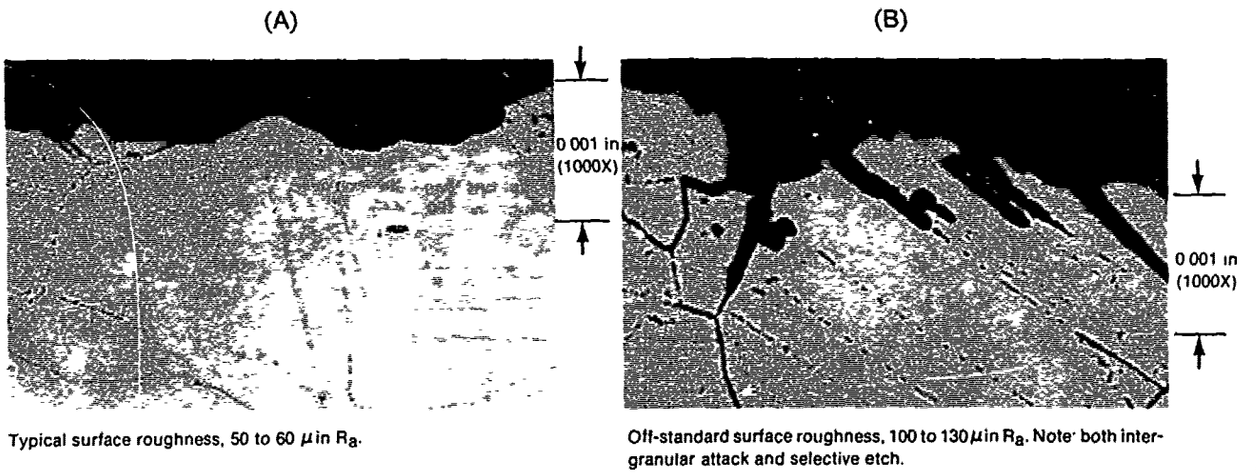


Figure 18.3-99 Comparison of surfaces of Rene 41 (45 R_C) when chemically machined in (A) solution treated state and (B) solution treated and aged state. (G. Bellows[23])

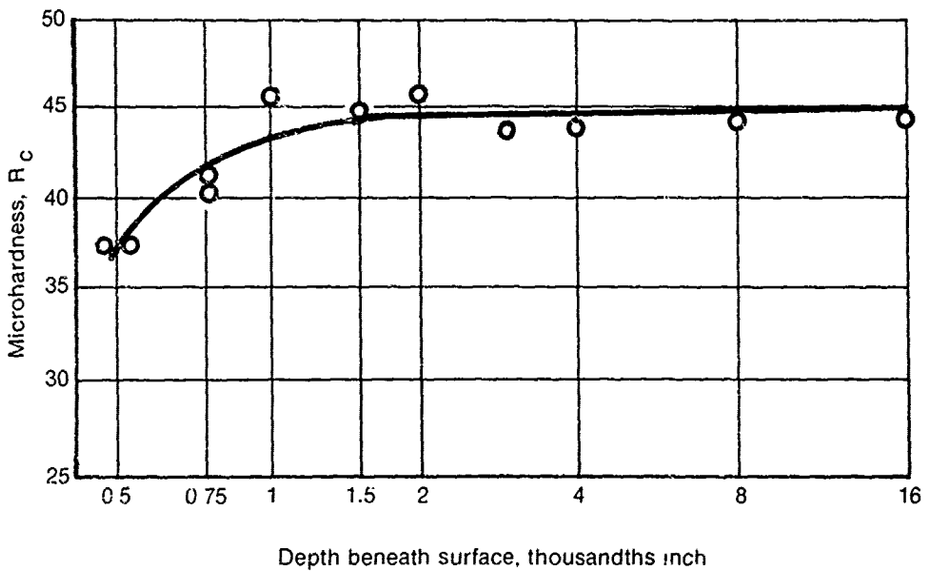


Figure 18.3–100 Rebinder (softening) effect on chemically machined Rene 41 (solution treated and aged), surface roughness 190 to 290 microinches R_a. (G. Bellows[23])

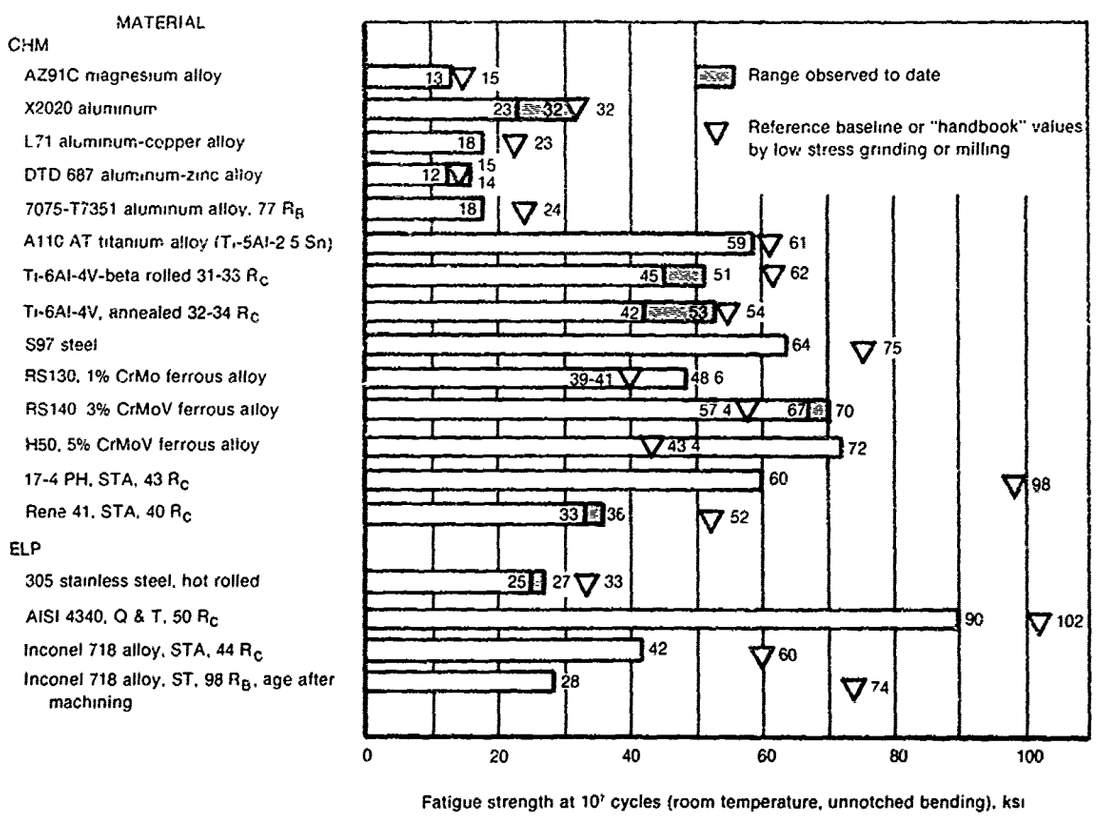


Figure 18.3–101 Summary of high cycle fatigue strength from chemical machining (CHM) and electropolishing (ELP). (G. Bellows[23])

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TABLE 18.3-24 Surface Integrity Effects Observed in Chemical Material Removal Processes

PROPERTY AND TYPE OF EFFECT	FINISHING, "GENTLE" OR LOW STRESS CONDITIONS		ROUGHING, "OFF-STANDARD" OR ABUSIVE CONDITIONS	
Surface roughness:	μin R_a	μm R_a	μin R_a	μm R_a
Average range	63 to 250	1.6 to 6.3	125 to 500	3.2 to 12.5
Less frequent range	8 to 500	0.2 to 12.5	63 to 500	1.6 to 12.5
Mechanical altered material zones:	inch*	mm*	inch*	mm*
Plastic deformation (PD)	***	***	***	***
Plastically deformed debris (PD²)	***	***	***	***
Hardness alteration†	0.0010	0.025	0.0031	0.079
Microcracks or Macrocracks	—	—	—	—
Residual stress‡	0.0010	0.025	0.0010	0.025
Metallurgical altered material zones:	inch*	mm*	inch*	mm*
Recrystallization	***	***	***	***
Intergranular attack (IGA)	0.0003	0.008	0.0060	0.152
Selective etch, pits, protuberances	0.0006	0.015	0.0015	0.038
Metallurgical transformations	—	—	—	—
Heat-affected zone (HAZ) or Recast layer	***	***	***	***
High cycle fatigue (HCF):	percent		percent	
Variation from "handbook" values at room temperature§	+18 to −39		−22 to −37	

SOURCE: G. Bellows and J. B. Kohls [20]

NOTE: A dash (—) in the table indicates no or insufficient data. A triple asterisk (***) in the table indicates no occurrences or not expected.

*Maximum observed depth normal to the surface.

†Depth to point where hardness becomes less than ±2 points R_c (or equivalent) of bulk material has (hardness converted from Knoop microhardness measurements).

‡Depth to point where residual stress becomes and remains less than 20 ksi [138 MPa] or 10% of tensile strength, whichever is greater.

§Handbook values from HCF testing frequently are generated from specimens that have been processed using low stress grinding, hand or gentle machine polishing or occasionally electropolishing. For this table, "handbook" values represent HCF strength values generated from low-stress-ground specimens (with their minor amount of retained but enhancing compressive residual stress). The values are the 10⁷ cycle strengths from full-reverse bending tests at room temperature.

Specific Guidelines and Data for POST-TREATMENT Processes to Aid Surface Integrity

Finishing operations or post-treatment processing have long been used in manufacturing. These operations are used to improve the surface roughness or appearance, to remove undesirable surface layers, or to enhance the beneficial compressive layers. The surface integrity produced by these finishing processes, or sequence of processes, should be assessed with the same diligence as that used for the prime fabricating process. While shot peening has been the most extensively used post treatment, consideration should be given to other techniques to achieve the desired effects. Often, other treatments may be used that result in less cost or greater productivity or better quality assurance. Some of the effective post-treatment processes are as follows:

AFM Abrasive flow machining
CBN Roller burnishing
CBS Belt sanding
CGH Hand grinding
CHM Chemical machining
CHN Honing
CPE Peening—shot, sand
CPG Glass bead peening
CPO Buffing
CTB Abrasive barrel tumbling
CVD Chemical vapor deposition
ECD Electrochemical deburring
ECP Electrochemical polishing
ELP Electropolishing
HT Heat treatment
LSG Low stress grinding
LST Laser shock treatment
USC Ultrasonic cleaning
USP Ultrasonic peening
VSR Vibration stress relief

Very gentle, low energy intensity conventional turning, milling or reaming can be quite effective as finishing operations; however, on stress-critical areas these processes should be carefully evaluated as previously detailed. Process and/or quality control must be rigorous and continuous with much insistence on the use of sharp tools Chemical and electrochemical processes with their absences of residual stress need special evaluation if it is desirable to add residual stress or cold working.

Figure 18.3-102 shows the shot peened surface of 18% nickel maraging steel Grade 250. Figure 18.3-103 illustrates the surface section of solution treated and aged Inconel Alloy 718 after shot peening, with off-standard ECM as the primary material removal method. Figure 18.3-103 depicts two levels of peening: level 1, using S110 shot of 50 to 55 R_C hardness with 300 percent coverage to Almen strip intensity of 0.006 to 0.008 A; and level 2, which was the same peening as level 1 except coverage was 125 percent

Figure 18.3-104 charts the residual stress pattern induced in solution treated and aged Inconel Alloy 718. The low-stress-ground specimens, 0.076 inch by 0.75 inch by 4 inches (approx. 2 mm by 20 mm by 100 mm), were shot peened with S110 steel shot to Almen intensity level 0.006 to 0.008 A. The residual stress profiles were prepared on specimens after exposure to the indicated temperatures for 100 hours in a vacuum. The shot peening pattern is essentially retained through 1300°F (704°C) for Inconel Alloy 718. This results in a 6 to 16 percent improvement in high cycle fatigue strength at 1000°F (538°C). On such specimens, an overpeened (that is, damaged) condition can occur when a 0.012- to 0.014-A intensity level is used on thin specimens such as these.

Figure 18.3-105 summarizes the high cycle fatigue strengths found for various materials subsequent to shot peening. These data are comparable to those illustrated for the material removal processes. Most of the tests were run on specimens peened to 0.006 to 0.008 A_2 or 0.004 to 0.006 A_2 on the Almen strip scale with 125 to 300 percent coverage.

Figure 18.3-106 summarizes the high cycle fatigue strength found with several types of post-processing treatments on one alloy, Inconel Alloy 718.

Post-Treatment Guidelines that Promote Good Surface Integrity Results

1. Careful washing should be employed to remove all traces of fluids used during machining that could contribute to stress corrosion.

2. Low temperature heat treatment will remove any hydrogen picked up during processing.

3 Heat treatments following material removal are of limited usefulness.

4. Abrasive tumbling can be effective for improving surface texture and for adding a modest compressive residual stress to aid fatigue strength.

5. Peening with steel shot or sand or glass beads can be useful to add substantial beneficial compressive residual stress, improve surface cleanliness and enhance fatigue strength

6. Mechanically gentle processing can be effective with specific evaluation of each situation

7. The benefits of shot peening can be nullified or severely decreased by exposure to high local stresses or temperatures or by vibration which allows the surface stress to relax by plastic deformation either from creep or yielding during "post-peen" processing or during operation.

8. The possibility that peening, burnishing, lapping and similar processes can cover up, but not overcome, the existing microcracks should be assessed.

9. Human variability means that hand finishing should be avoided if possible or controlled rigorously.

10 It is possible to overpeen surfaces and create excessive core stresses, microcracks, untempered martensite, laps or similar abuses.

11. The junction between peened and unpeened surfaces should be "feathered" to avoid stress concentrations.

Special Comments Concerning Surface Integrity Practices for Post-Treating Processes

Cracks, heat-affected and other detrimental layers created during material removal processes should be removed (or altered) from critically stressed areas of component parts. Microstructural examination and microhardness testing can frequently establish the depth of adversely altered layers and other defects. Certain critical situations may require mechanical testing to be certain that no alterations have been produced which cannot be detected by microexamination. Removal of these defective layers by gentle processes should be accomplished. Some post-treatment processes can satisfactorily alter these layers or even enhance the fatigue strength results.

Steel shot and glass bead peening as well as burnishing can be used to improve surface integrity. A considerable number of studies have confirmed that the fatigue life determined in laboratory tests and verified by field performance is measurably enhanced by peening.[8] Laboratory tests have shown that shot peening is effective in substantially increasing high cycle and low cycle fatigue strength at both room and elevated temperatures for typical titanium alloys, high temperature alloys, and high strength steels, regardless of the type of prior material removal processing. For example, electrical discharge machining and abusive grinding are two processes which are among the most detrimental to these alloy groups. But when added as a post-processing treatment, shot peening has been shown capable of fully restoring the room and elevated temperature low cycle and high cycle fatigue strengths for these alloy groups. Since the above comments are based upon laboratory tests of specimens, component evaluations are recommended. Peening, which puts the surface layer into compression and cold works the surface,

must be performed under controlled conditions Specifications for controlled peening should include consideration of factors such as the cleanliness and surface roughness of the part being machined; the type, the chemistry, the geometry and the hardness of the shot and its fluid carrier; and peening time, intensity and coverage. Reports also indicate that peening improves resistance to corrosion and reduction in stress corrosion susceptibility. There are indications that cold working of drilled holes by burnishing is also beneficial as is roller burnishing. Some reports contain precautions against overpeening in order to avoid fatigue damage and to reduce the possibility of masking flaws such as fine cracks.

Evaluate the use of controlled shot peening practices to restore fatigue life of components processed by electrical, chemical, and thermal removal processes. Shot peening has been shown to be extremely effective in improving the fatigue life of *specimens* processed by electrochemical machining (ECM), electrical discharge machining (EDM), and electropolishing (ELP).[9] Component tests are recommended to confirm the favorable trends shown in tests on laboratory specimens. Examples of shot peening improvement in the fatigue strength of specimens are shown in table 18 3-25.

Post heat treatments following material removal are of limited usefulness. Stress relief treatments, used to soften hardened layers produced during grinding of steels, do not restore the hardness of overtempered layers which are present immediately below the damaged surface layers. Also, heat treatment does not heal any cracks produced during material removal. Some companies have advised the use of tempering operations to relieve stresses after electrical discharge machining (EDM) of steels. Stresses may be relieved but fatigue properties are not improved sufficiently. Evidence has also been presented to show that annealing treatments following EDM on nickel base alloys, such as Rene 41, Inconel Alloy 625, Inconel Alloy 718 and Monel Alloy K-500, seriously lower tensile strength and ductility as a result of carbon diffusion.[10] Experience has shown that heat treatments in some cases have improved surface integrity of damaged surfaces but not nearly as effectively as shot peening Low temperature heat treatments are helpful in eliminating embrittlement for operations where hydrogen may be picked up during processing, such as in plating. Elimination of hydrogen is time- and temperature-dependent and also depends upon the alloy being treated. Steels, for example, are often treated at about 375° to 400°F [191° to 204°C] for periods of 8 hours or more.

Abrasive tumbling is an effective process for improving surface properties including fatigue. This process is less applicable than shot peening for many of the very large parts required for aerospace applications Both abrasive tumbling and shot peening usually require an added polishing operation when very high finish requirements must be satisfied. Care must be taken not to remove the thin favorable surface layer established by peening or tumbling. Abrasive tumbling can be used to reverse unfavorable tensile stresses by inducing a compression stressed surface layer.

Washing procedures should be employed for critical parts and assemblies to remove all traces of cutting fluids which may cause corrosion. Typical suspect compounds are sulfur compounds on aluminum and nickel base alloys and chlorine compounds on titanium alloys.[11] Currently, some companies do not allow any chlorine-containing cutting fluids to be used in processing titanium parts which are to be used at room or elevated temperatures. Other companies use this precaution only for parts which are subjected to temperatures over 500°F [260°C]. For applications at less than 500°F [260°C], carefully controlled washing procedures are often used to remove the chlorinated and sulfurized cutting oils. These fluids are particularly effective for chip removal operations such as drilling, tapping and broaching. Since complete agreement does not exist among manufacturers regarding cutting fluid practices, subcontractors are obliged to follow the policies and procedures established by the prime contractor.

Protection of parts. Parts should not be stored for extended periods without being carefully washed and then covered with a coating of oil for corrosion prevention.

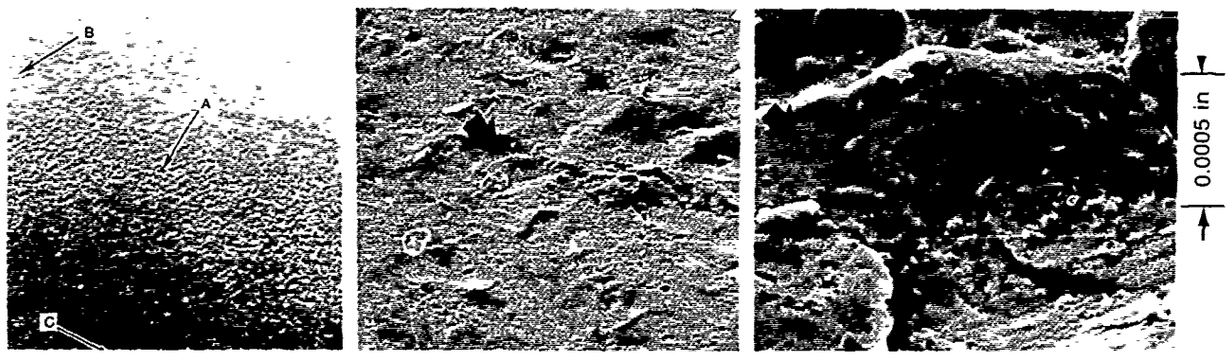


Figure 18.3–102 Typical surface characteristics of shot-peened Grade 250 Maraging steel. Surface machined with ECM, then 300% coverage shot peened with S110 shot of 45 to 50 R_C hardness to Almen level 0.004 to 0.006 A_2. View by SEM at 45° at increasing magnifications of 20, 200 and 2000X. Note impression of single shot in highest magnification view. Surface roughness of 38 microinches R_a. (Surface Integrity Encyclopedia[1])

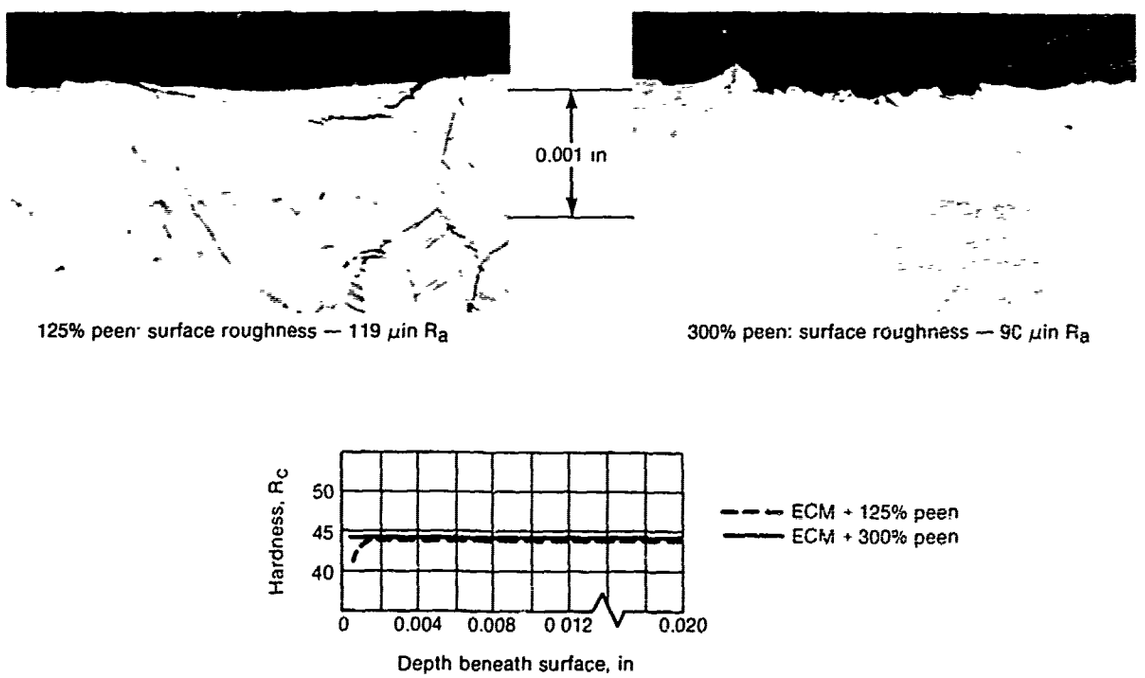


Figure 18.3–103 Surface characteristics of Inconel Alloy 718 (solution treated and aged, 44 R_C) produced by ECM plus shot peening. Note roughness similar to ECM but with additional tears and cracks, perhaps from peening. Subsurface strain lines from peening also visible. (W. P. Koster et al[8])

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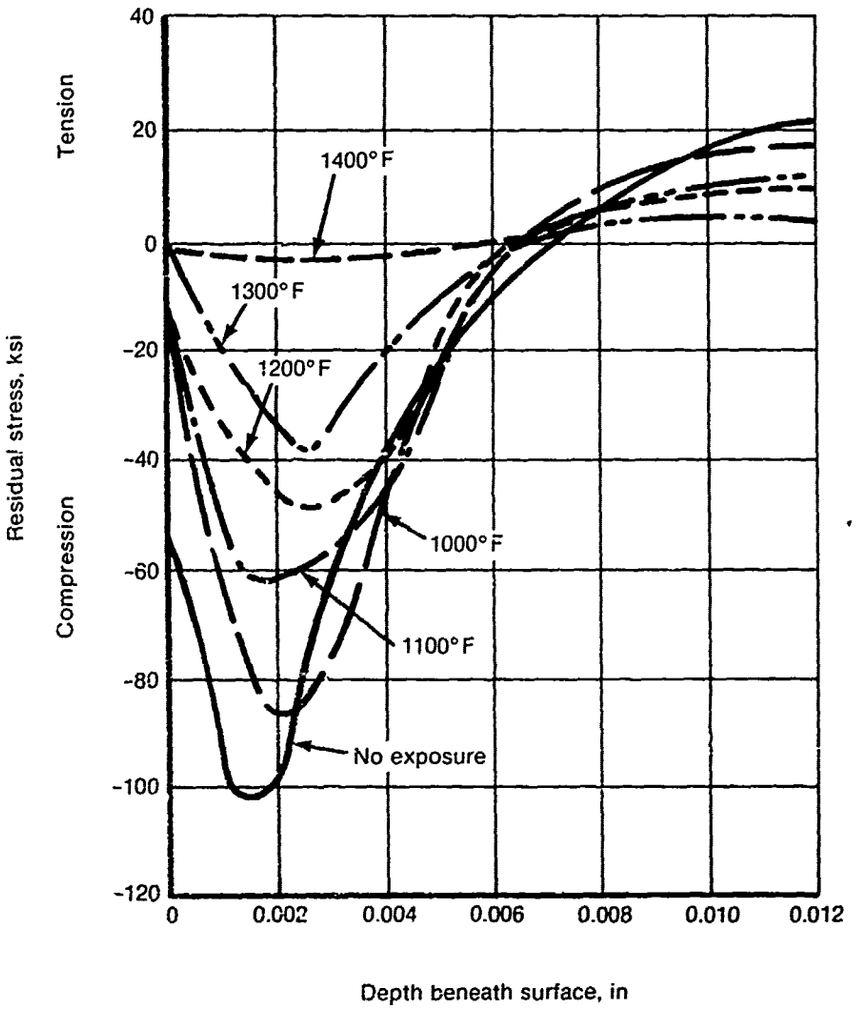


Figure 18.3-104 Residual stress patterns in Inconel Alloy 718 (solution treated and aged) produced by low stress grinding plus peening (0.006- to 0.008-A intensity) after 100-hour exposure to various elevated temperatures. (G. Bellows and R. M. Niemi[24])

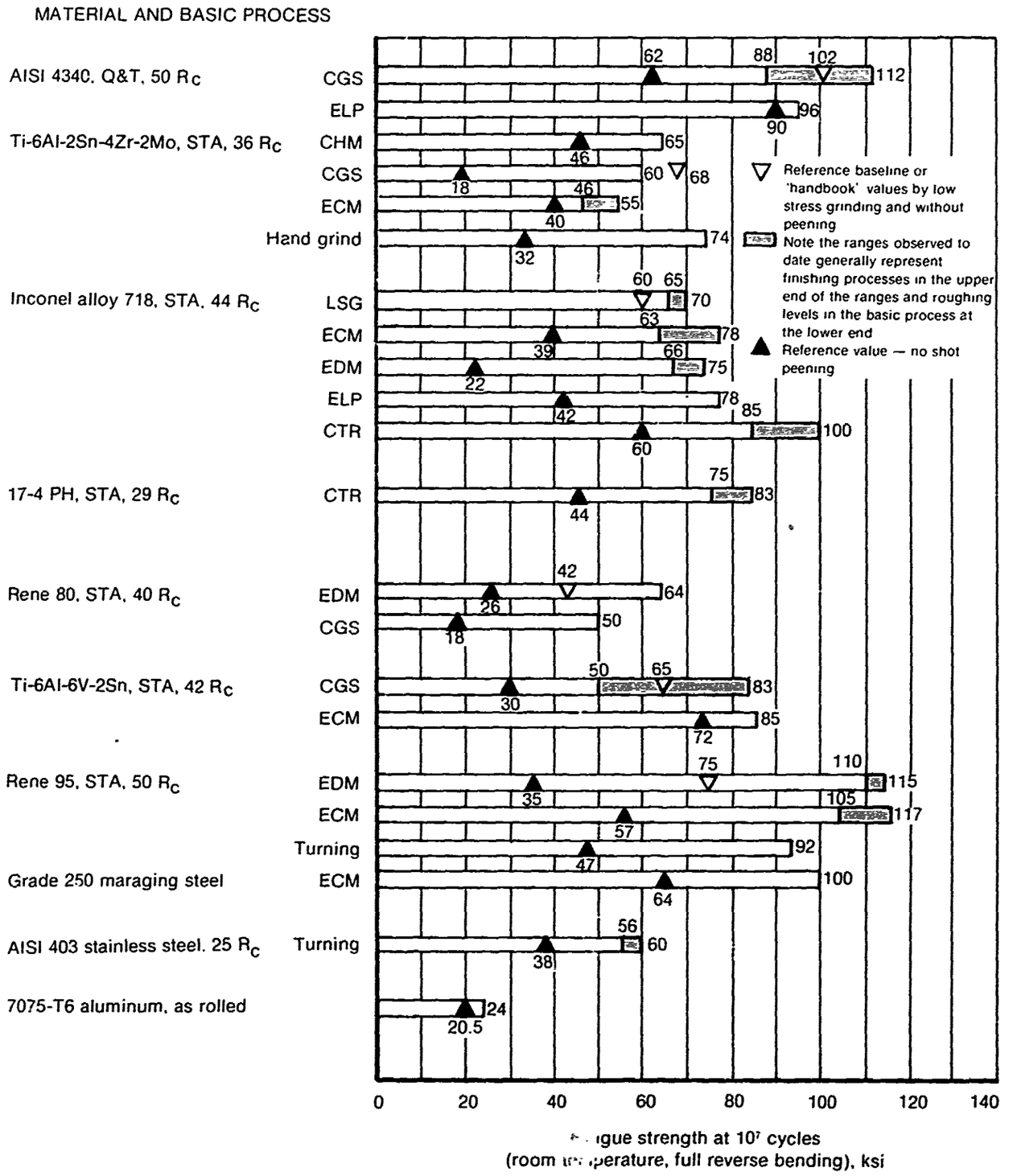


Figure 18.3–105 Summary of high cycle fatigue strength of materials shot peened subsequent to basic material removal process.

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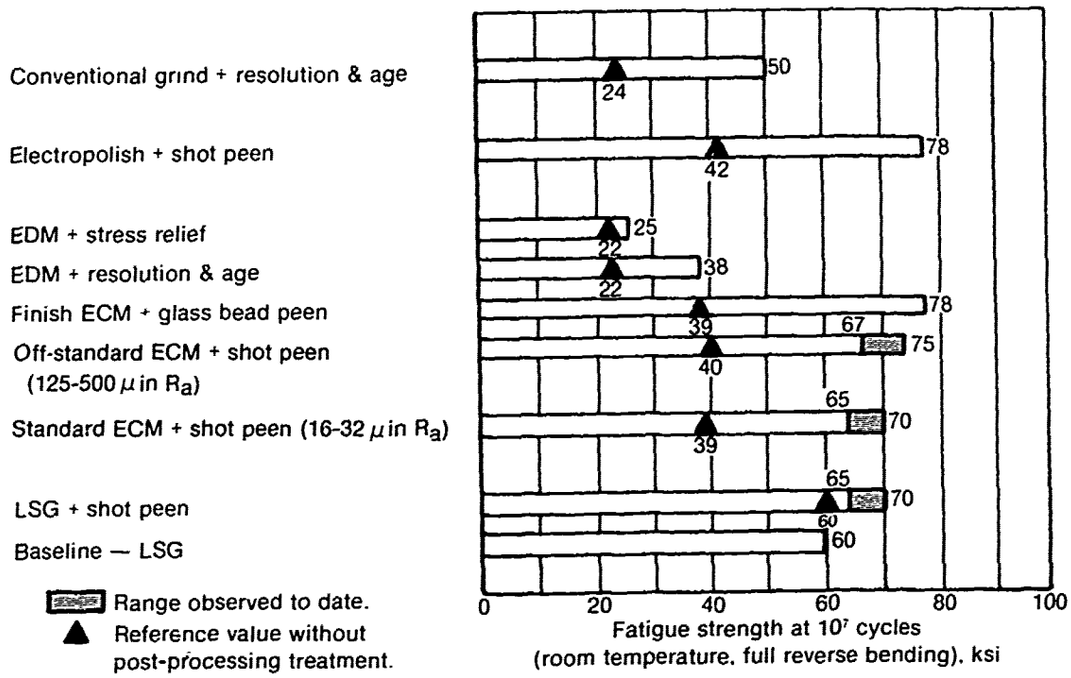


Figure 18.3-106 Summary of high cycle fatigue strength of Inconel Alloy 718 (solution treated and aged) with several types of post-processing treatments. Baseline reference, or "handbook" value, from low stress grinding (LSG).

TABLE 18.3-25 Fatigue Strength Comparisons for Materials Processed With and Without Shot Peening

MATERIAL AND PROCESS	FATIGUE STRENGTH*			
	Without Peen		With Peen	
	ksi	MPa	ksi	MPa
AF 95 (STA, 50 R_c)				
ECM	57	393	105	724
EDM	40	276	115	793
Low stress or Gentle grinding	75	517	—	—
Inconel 718 (STA, 44 R_c)				
ECM	39	269	78	538
ELP	42	290	78	538
Low stress or Gentle grinding	60	414	—	—
Ti-6Al-6V-2Sn (STA, 42 R_c)				
ECM	72	496	65	448
Low stress or Gentle grinding	65	448	—	—

*Room temperature, 10^7 cycles full-reverse bending.

SURFACE INTEGRITY BY MATERIALS—HIGH CYCLE FATIGUE RESULTS

It is helpful in selecting the processes to be used in fabricating a component part to compare the relative fatigue strengths from a variety of processes. Value engineering can be strengthened by use of surface integrity data to assure a more complete and disciplined approach to process selection. Tables 18.3-7, 18.3-8, and 18.3-26 to 18.3-30 provide such data for a number of alloys. Caution and restraint should be exercised before transferring these data to similar alloys. It has been found that each intensity level of a process will have a unique surface integrity response for each metallurgical state of the work material. The data presented are the room temperature high cycle fatigue strength at 10^7 cycles taken from full-reverse bending tests.

TABLE 18.3-26 Comparative Fatigue Strengths and Surface Roughnesses of 4340 Steel (Quenched and Tempered 50 R_c) from Several Processes

PROCESS	FATIGUE STRENGTH*		SURFACE ROUGHNESS	
	ksi	MPa	μin R_a	μm R_a
Grinding:				
Gentle longitudinal surface grinding	117	807	8	0.20
Gentle longitudinal surface grinding	110	758	65	1.60
Gentle longitudinal surface grinding	100	689	127	3.20
Gentle traverse surface grinding	120	827	11	0.28
Gentle traverse surface grinding	100	689	58	1.50
Gentle traverse surface grinding	85	586	128	3.30
Low stress surface grinding (LSG)	102	703	45	1.10
Conventional surface grinding	70	483	40	1.03
Abusive grinding	62	427	50	1.25
Abusive longitudinal surface grinding	65	448	28	0.70
Abusive longitudinal surface grinding	65	448	64	1.60
Abusive longitudinal surface grinding	65	448	97	2.50
Low stress grinding plus shot peen	112	772	25	0.63
Abusive grinding plus shot peen	88-92	607-634	40-76	1.00-1.90
Gentle hand sanding	94	648	115	2.90
Abusive hand sanding	98	676	105	2.70
Abusive hand sanding plus shot peen	118	556	56	1.40
Milling:				
Finish end milling—end cut	85	586	75	1.90
Rough end milling—end cut	72	496	71	1.80
Chemical NTM:				
Electropolishing (ELP)	90	621	15	0.40
ELP plus shot peen	96	662	46	1.20

*Room temperature, 10^7 cycles full-reverse bending.

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TABLE 18.3-27 Comparative Fatigue Strengths and Surface Roughnesses of Ti-6Al-4V from Several Processes

MATERIAL CONDITION AND PROCESS	FATIGUE STRENGTH*		SURFACE ROUGHNESS	
	ksi	MPa	μin R_a	μm R_a
BETA ROLLED 32 R_c				
Grinding:				
Low stress surface grinding	62	427	35	0.90
Conventional surface grinding	12	83	45	1.1
Abusive surface grinding	13	90	65	1.60
Gentle hand sanding	57	393	80	2.0
Abusive hand sanding	30	207	80	2.0
Milling:				
End milling—sharp cutter	64	441	67	1.70
End milling—dull cutter	77	531	84	2.10
Peripheral milling—sharp cutter	70	483	17	0.40
Peripheral milling—dull cutter	32	221	59	1.50
Chemical NTM:				
Standard CHM	51	352	20	0.50
Off-standard CHM	45	310	165	4.20
SOLUTION TREATED AND AGED				
Electrical NTM:				
Standard ECM	60	417	14	0.35
Off-standard ECM	40	276	165	4.20
ANNEALED 32-34 R_c				
Grinding:				
Low stress surface grinding	54	372	24	0.60
Conventional surface grinding	12	83	30	0.75
Abusive surface grinding	14	97	48	1.20
Turning:				
Gentle turning	66	455	22	0.55
Rough turning	71	490	34	0.85
Milling:				
Gentle end milling—end cut	73	503	16	0.40
Rough end milling—end cut	64	441	20	0.50
Chemical NTM:				
Standard CHM	53	365	18	0.45
Off-standard CHM	42	290	157	3.90
Thermal NTM:				
EDM	24	165	69	1.75

*Room temperature, 10^7 cycles full-reverse bending.

TABLE 18.3-28 Comparative Fatigue Strengths and Surface Roughnesses of Ti-6Al-2Sn-4Zr-2Mo (Solution Treated and Aged 36 R_c) from Several Processes

PROCESS	FATIGUE STRENGTH*		SURFACE ROUGHNESS	
	ksi	MPa	μin R_a	μm R_a
Grinding:				
Low stress surface grinding (LSG)	68	469	39	1.00
Conventional surface grinding	17	117	41	1.00
Abusive surface grinding	10	69		
Hand grinding	32	221	120	3.00
LSG plus age	50	345		
Conventional surface grinding plus shot peen	60	414		
Hand grinding plus stress relief	44	303		
Hand grinding plus shot peen	74	510		
Milling:				
Gentle milling—peripheral cut	82	565	36	0.90
Rough milling—peripheral cut	47	324	77	1.90
Electrical NTM:				
Standard ECM	40	276	32-125	0.80-3.20
Off-standard ECM	25	172	125-500	3.20-12.50
STEM	35	241		
Standard ECM plus shot peen	55	379		
Off-standard ECM plus shot peen	46-50	317-345		
Chemical NTM:				
ELP	50	345		
CHM	46	317		
CHM plus shot peen	65	448		

*Room temperature 10^7 cycles full-reverse bending.

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TABLE 18.3-29 Comparative Fatigue Strengths and Surface Roughnesses of Inconel Alloy 718 (Solution Treated and Aged 44 R_c) from Several Processes

PROCESS	FATIGUE STRENGTH*		SURFACE ROUGHNESS	
	ksi	MPa	μin R_a	μm R_a
Grinding:				
Low stress surface grinding (LSG)	60	414	15	0.38
Conventional surface grinding	24	165	26	0.65
Abusive surface grinding	22	152	70	1.75
Hand grinding	40	276	64	1.60
LSG plus resolution and age	58	400	15	0.38
LSG plus superfinish and age	49	338	<5	<0.125
LSG plus vacuum age	74	510	17	0.43
LSG plus shot peen	65-70	448-483		
LSG plus shot peen	70	483	—	—
Conventional surface grinding plus resolution and age	50	345	26	0.65
Conventional surface grinding plus stress relief	58	400	—	—
Hand grinding plus stress relief	40	276	32	0.80
Turning:				
Gentle face turning	60	414	25	0.63
Gentle face turning	60	414	58	1.45
Gentle face turning	60	414	188	4.70
Abusive face turning	60	414	76	1.90
Conventional turning—Borazon® CBN tool	85	586	39	1.00
Conventional turning—Carbide	55	379	65	1.60
Electrical NTM:				
Standard ECM	39-40	269-276	43	1.10
Off-standard ECM	39-40	269-276	74-500	1.9-12.5
STEM	39	269	125	3.20
Standard ECM plus vacuum age	42	290	19	0.49
Off-standard ECM plus vacuum age	42	290	55	1.38
Standard ECM plus glass bead peen	78	538	69	1.70
Standard ECM plus shot peen	65-78	448-538	74	1.90
Off-standard ECM plus shot peen	67-75	462-517	90-119	2.25-3.00
Thermal NTM				
Finish EDM	22	152	60	1.50
Rough EDM	22	152	170	4.30
Finish EDM plus vacuum age	29	200	65	1.60
Rough EDM plus vacuum age	29	200	155	3.90
Rough EDM plus resolution and age	26-38	179-262	175	4.40
Rough EDM plus stress relief	25	172	221	5.50
Finish EDM plus glass bead peen	66	455	43	1.10
Rough EDM plus shot peen	75	517	125	3.20
Chemical NTM:				
CHEM	40	276	16	0.40
ELP	40-42	276-290	15	0.40
ELP plus shot peen	78	538	43	1.10
ELP plus vacuum age	28	193	15	0.40

*Room temperature, 10⁷ cycles full-reverse bending

TABLE 18.3-30 Comparative Fatigue Strengths and Surface Roughnesses of Rene 80 (Solution Treated and Aged) from Several Processes

PROCESS	FATIGUE STRENGTH*		SURFACE ROUGHNESS	
	ksi	MPa	μin R_a	μm R_a
Grinding.				
Low stress grinding (LSG)	42-43	290-296	16	0.40
Conventional grinding	18	124		
Abusive grinding	16	110		
Low stress grinding—finishing plus age heat treat	33-40	228-276		
Low stress grinding—finishing plus full heat treat†	35	241		
Low stress grinding—finishing plus full heat treat and shot peen†	53-57	365-393		
Conventional grinding—roughing plus age heat treat	32-35	221-241		
Conventional grinding—roughing plus full heat treat†	33-36	228-248		
Conventional grinding—roughing plus full heat treat and shot peen†	54	372		
Ultra-high speed grinding plus vacuum heat treat	40	276		
Ultra-high speed grinding plus shot peen	50	345		
Electrical NTM:				
Standard ECM conditions	28	193	30	0.50
Off-standard ECM conditions	28	193	40	1.00
Finish ECG	30	207		
Rough ECG	30	207		
Thermal NTM.				
Finish EDM	24-26	165-179	70	1.75
Rough EDM	22-26	152-179	150	3.75
Solution treat plus EDM	25	172		
EDM plus resolution and age	32	221		
EDM with recast removed by LSG	34	234		
EDM plus shot peen	64	441		

*Room temperature, 10⁷ cycles full-reverse bending
† Full heat treatment includes aging plus equivalent of brazing and coating cycles

QUALITY ASSURANCE FOR SURFACE INTEGRITY

Quality control practices should be reviewed and amplified in order to satisfy high surface quality requirements. No instrument exists that will measure surface integrity. Properties which may require investigation in order to establish surface integrity include surface texture, surface metallurgy, mechanical properties, surface chemistry and other engineering properties. Table 18.3-31 is a summary of standard and specialized techniques generally employed for these measurements.

It is advisable to become acquainted with the possible types of surface alterations which result from the combination of a metal removal process with a specific material. Information of this type is provided in tables 18.3-2 and 18.3-32. Nondestructive testing is the most desirable approach to evaluating surface integrity effects. The principal nondestructive testing methods for evaluating surface integrity and subsurface characteristics are listed in tables 18.3-33 and 18.3-34. Destructive techniques are also shown in table 18.3-34 for comparison.

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TABLE 18.3-31 Techniques for Surface Integrity Measurement

PROPERTY	STANDARD TECHNIQUES	SPECIALIZED TECHNIQUES
Surface Texture	Contact (tracer point or stylus measurement)—Linear traverse or area traverse	Noncontact measurements— Optical Microscopy Interference microscopy, etc Three dimensional surface profile by combination of roughness measurement and computer plotting Scanning electron microscopy
Surface Metallurgy Microstructure	Metallurgical sectioning—Optical microscopy	Transmission electron microscopy
Microhardness	Microhardness testing—Knoop or Vickers indenter	
Microcracks and Crevice-like defects	Metallurgical sectioning—Optical microscopy Nondestructive—Macroetching Penetrant inspection etc.	Scanning electron microscopy Nondestructive—Eddy Current Ultrasonic etc.
Static Mechanical Properties Tensile strength & Ductility	Tensile testing	
Stress rupture & Creep	Creep testing	
Residual stress	X-ray diffraction Layer removal—Curvature measurement	
Stress corrosion	*Steels & Aluminum:* Constant prestress with alternate immersion in salt solution and air *Titanium:* Specimen coated with salt or halide and exposed to high temperature and stress	Stress corrosion crack propagation testing
Fracture toughness		Fracture toughness testing
Dynamic Mechanical Properties High cycle fatigue	Bending fatigue testing, $A^* = \infty$	Axial fatigue testing, $A^* = 0.95$
Low cycle fatigue	Bending fatigue testing, $A = \infty$	Axial fatigue testing, $A = 0.95$
Surface Chemistry	Electron microprobe analysis Dissolution of the surface layer by chemical or electrochemical etching followed by spectroscopy, spectrophotometry, etc.	Electron spectroscopy—Electron spectroscopy for chemical analysis (ESCA) Auger spectroscopy Ion spectroscopy— Ion scattering spectrometry Ion probe mass spectroscopy
Other Engineering Properties Friction Wear Fretting Galling & Seizing Corrosion Reflectivity Electrical properties Etc.	A variety of standard and specialized techniques have been developed to evaluate these properties for specific applications	

SOURCE: M. Field, J. F. Kahles and J. T. Cammett.[12]

*A = ratio of dynamic/static stress

TABLE 18.3-32 Surface Hardness Changes That May Result from Various Metal Removal Processes

MATERIAL	CONVENTIONAL PROCESSES		NONTRADITIONAL PROCESSES			
	Milling, Drilling, Turning, or Grinding		EDM		ECM or CHM	
	Surface Alteration	Hardness Change	Surface Alteration	Hardness Change	Surface Alteration	Hardness Change
Steels	PD UTM OTM RS OA	Increase Increase Decrease Decrease Decrease	RC UTM OTM RS OA	Increase Increase Decrease Decrease Decrease	None	Decrease
Nickel- and Cobalt-base superalloys	PD	Increase	RC	Increase	None	Decrease
Titanium alloys	PD	Increase	RC	Increase	None	Decrease
Refractory alloys (TZM, Tungsten)			RC	No change	None	Decrease

SOURCE: M. Field, J. F. Kahles and J. T. Cammett.[2]

Key: PD — Plastic deformation and plastically deformed debris
UTM — Untempered martensite
OTM — Overtempered martensite
RS — Resolution or austenite reversion
OA — Overaging
RC — Recast, resplattered metal or vapor deposited metal

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TABLE 18.3-33 Nondestructive Techniques for Detecting Surface Inhomogeneities in Metals

TECHNIQUE	APPLICATION	STATUS
1 Visual Inspection	Surface defects	Widely employed
2 Automatic Optical Scanning	Surface defects	Specialized
3 Dye Penetrant	Surface defects	Widely employed
4 Magnetic Particle	Surface defects	Widely employed
5 Acid Macroetch	Crack detection	Widely employed
	Surface phase transformations	Widely employed
	Redeposited & resolidified metal	Widely employed
6. Eddy Current	Surface defects	Widely employed
	Inclusion & subsurface defects	Widely employed
	Surface hardness changes	Specialized
	Plastic deformation	Specialized
	Surface phase transformation	Needs development
	Subsurface fatigue	Needs development
	Residual stress analysis	Needs development
7 Ultrasonic Pulse Echo	Inclusions & subsurface defects	Widely employed
	Surface defects	Specialized
8. Ultrasonic Velocity	Residual stress analysis	Specialized
	Surface phase transformation	Needs development
	Plastic deformation	Needs development
9 Ultrasonic Attenuation	Recrystallization & grain growth	Specialized
	Residual stress analysis	Needs development
10. High Frequency Ultrasonic	High resolution of surface defects	Specialized
11. X-Ray Radiography	Subsurface defects	Widely employed
12 X-Ray Diffraction	Residual stress analysis	Widely employed
	Surface phase transformation	Specialized
13. X-Ray Spectroscopy	Composition changes	Needs development
14. Neutron Radiography	Subsurface defects	Specialized
15. Gamma Radiography	Subsurface defects	Specialized
16 Radioactive Gas Penetrant	Surface defects	Needs development
	Recrystallization & grain growth	Needs development
	Plastic deformation	Needs development
	Subsurface defects	Needs development
17. Surface Electrical Resistance	Surface defects	Needs development
	Surface phase transformation	Needs development
18 Beta Backscatter	Surface hardness changes	Needs development
	Plastic deformation	Needs development
19. Electrochemical Potential	Residual stress analysis	Needs development
20. Laser Probe Mass Spectrometry	Surface composition	Needs development

SOURCE: M. Field, J. F. Kahles and J. T. Cammett [12]

TABLE 18.3-34 Testing Techniques Used To Detect and Locate Surface Inhomogeneities in Metals

METALLURGICAL INHOMOGENEITY	NONDESTRUCTIVE TECHNIQUES			DESTRUCTIVE TECHNIQUES
	Commonly Employed	Specialized	Possible With Further Developments	
Macrocracks	Visual inspection Binocular inspection Magnetic particle Penetrant Eddy current Acid macroetch	Ultrasonic pulse echo Automatic optical scanning	Acoustic impact	Optical metallography
Microcracks	Binocular inspection High sensitivity fluorescent penetrant Magnetic particle	Ultrasonic pulse echo, surface waves and lamb waves	Radioactive gas penetrant High frequency ultrasonic Acoustic impact Surface electrical resistance	Optical metallography Scanning electron microscopy Transmission electron microscopy
Tears, laps & pits	Visual with etch Magnetic particle Eddy current Penetrant	Automatic optical scanning	Radioactive gas penetrant	Optical metallography Scanning electron microscopy
IGA & selective etch		High sensitivity fluorescent penetrant		Macroetch Optical electron microscopy Transmission electron microscopy
Surface phase transformation (OTM, UTM, resolutioning, etc)	Macroetch	X-Ray diffraction Magnetic particle	Ultrasonic velocity Surface electrical resistance Eddy current	Optical metallography
Composition changes (oxidation, decarb, etc)			Laser probe Mass spectrometry X-Ray spectroscopy	Wet chemical analysis Electron microprobe
Surface hardness changes	Superficial hardness testing Ultrasonic hardness testing	Eddy current X-Ray diffraction	Beta backscatter	Microhardness traverse
Redeposited & resolidified metal	Macroetch Visual inspection			Optical metallography
Recrystallization & grain growth		Ultrasonic attenuation	Radioactive gas penetrant	Optical metallography
Plastic deformation (cold work, hot work)	Superficial hardness testing	Eddy current Magnetic particle	Beta backscatter Radioactive gas penetrant Ultrasonic velocity	Optical metallography Microhardness traverse
Inclusions & voids	Ultrasonic pulse echo shear wave, surface wave, and lamb wave Penetrant X-Ray radiography Eddy current Magnetic particle	Gamma radiography Neutron radiography	Radioactive gas penetrant	Optical metallography
Residual stresses	X-Ray diffraction	Ultrasonic velocity	Eddy current Electrochemical potential Ultrasonic attentuation Magneto-absorption	Parting-out Layer removal X-Ray diffraction
Distortion	Visual inspection	Metrology		

SOURCE: M. Field, J. F. Kahles and J T. Cammett [7]

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After exhausting the nondestructive testing methods, reliance is then placed on destructive testing of extra workpieces or coupons by simulating the process factors In some situations, it is necessary to resort to detailed process parameter planning followed up by operator education and periodic audits for compliance to the preplanned conditions Few quality assurance engineers are fully satisfied with a process control approach; however, it can be effective—if production supervision exercises a relentless insistence upon performance according to standards

It is vital to surface integrity that as much attention be placed on the quality of the material presented for processing as is placed upon process parameter control. The metallurgical state will affect the final "as-shipped" surface quality as much as the intensity level at which the process is operated. Similarly the *full* sequence of operations applied to a surface must be evaluated, and the evaluation must be made with the *exact* sequence used during production.

The best quality assurance is the evaluation of surfaces of specific parts when exposed to the full environmental effects expected; namely, heat, chemicals, stress, vibration, etc The minimum data set can provide a better evaluation, but the extended data set is recommended for the most critically loaded or exposed surfaces. This controlled, systematic testing technique is recommended for safety critical areas of component parts.

Specific Guidelines and Special Comments on Quality Assurance for Surface Integrity

1. Detection of Untempered and Overtempered Martensite

Parts manufactured from martensitic high strength steel can be visually inspected after an acid etch for evidence of untempered or overtempered martensite (frequently found from grinding and some forms of mechanical cutting). Typically, untempered martensite appears white and overtempered areas appear darker than the background material A specific etching technique for detecting grinding damage in hardened steel is given in table 18.3-35

2. Conventional Versus Nontraditional Processes

The original surface integrity investigations concentrated heavily on grinding and the nontraditional material removal processes like electrical discharge machining and electrochemical machining. More recently, the older, conventional, generally mechanical material removal processes have been shown to have an equal range of surface integrity effects It is vitally important that the application of surface integrity practices include an assessment of *every* process that effects the final, "as-shipped" surface.

3. Suggested Experimental Programs

Systematic metallurgical and mechanical testing programs for establishing and controlling surface integrity are essen-

TABLE 18.3-35 Etching Technique for Detecting Grinding Damage in Hardened Steel

OPERATION	SOLUTION USED	DESCRIPTION, TIME, OR FUNCTION
Double Etch Method		
(1) Etch No. 1	4 to 5% Nitric acid in water	Until black, 5 to 10 seconds. Do not over etch.
(2) Rinse	Warm water	To remove acid
(3) Rinse	Methanol (or acetone*)	To remove water
(4) Etch No. 2	5 to 10% Hydrochloric acid in methanol (or acetone*)	Until black smut is removed, 5 to 10 seconds
(5) Rinse	Running warm water	To remove acid
(6) Neutralize	2% Sodium carbonate + phenolpthalien indicator in water	To neutralize any remaining acid
(7) Rinse	Methanol	To remove water
(8) Dry	Warm air blast	
(9) Oil dip	Low viscosity mineral oil with rust inhibitor	Enhance contrast, prevent corrosion
Nital Etch Method		
(1) Etch	5 to 10% Nitric acid in ethanol or methanol	Until contrast is evident
(2) Repeat steps 5.9 above		

SOURCE: M Field, J. F Kahles and J T. Cammett [1]

NOTE: Dark areas on etched surfaces show overtempering, light areas show rehardening, and uniform gray indicates no injury.

*4% HNO_3 in water for Etch No 1 used with 2% HCl in acetone for Etch No. 2 sometimes gives greater sensitivity on high carbon hardened steel. It is important that appropriate precautions be taken to avoid fire hazards, and good ventilation must be provided

tial for highly critical parts and have been detailed previously. Functional testing of the final product of field testing under actual service conditions is a desirable step for the most critical applications

4. Comparative Photomicrographs

Comparison of current results during production with sets of photomicrographs that display both the "standard" and "off-standard" conditions to be expected are helpful. The growing data accumulations in surface integrity encyclopedias also are useful. The Machinability Data Center has the most extensive collection of this information. These data also are useful in appraising or establishing quality control limits or process parameter limits

5. Specifications

Several companies now have special specifications for processing to secure the best surface integrity. These are very helpful to the vendors for guidance and to quality control for measurement. These special specifications should be used with care and only for those portions or surfaces of a component part deemed critical, otherwise costs will rise unnecessarily. Standards for surface integrity are being prepared both by the American National Standards Institute (ANSI) and by the International Organization for Standardization (ISO)

6. Accidents Which Occur During Processing Should Be Reported to Quality Control

Operators should be instructed to notify supervisors of all accidents or damage including all visual evidence of damage. Grinding burn, breaking of drills, reamers or taps in holes, or shorting of electrodes in both electrical discharge machining and electrochemical machining are examples of the types of mishaps which should be reported. Cleanup of surface discoloration is not necessarily sufficient to remove all of the damage which may extend several thousandths inch below the surface, as demonstrated in figure 18.3-75. In case of damage, parts should be systematically reviewed.

7. Inspection Practices Should Be Reviewed and Amplified in order To Satisfy Surface Integrity Requirements

There are several nondestructive and destructive testing practices which are being employed to test surface conditions. Brief discussions of these practices are presented in the following:

a. Microscopic examination including microhardness testing is used on a sampling basis in order to determine the kind of surface layer being produced and its depth. This method may be used to check for microcracks, pits, folds, tears, laps, built-up edge, intergranular attack, sparking, etc. Since many surface alterations are shallow, it is essential to use good edge retention techniques for microscopic examination. See table 18.3-6.

b The white layer or overtempered martensite produced during grinding of steels can be detected by immersion etching using a 3 to 5 percent aqueous nitric acid solution. The procedures used vary among producers and are quite detailed and very exacting, consisting essentially of appropriate and specific precleaning, etching, and post-etching procedures, including cleaning, drying, and application of rust inhibitors, as outlined in table 18.3-35

c Magnetic particle inspection, penetrant inspection, ultrasonic testing, and eddy current techniques are recommended for detecting macrocracks. Most of the inspection techniques currently being used should be further refined by using more care in their application. Direct visual examination should be supplemented by macroscopic examination at low and medium magnifications (5 to 20X). Some of these methods require low levels of surface roughness on the surface being examined in order to reduce background "noise" to the instrument.

d. X-ray diffraction methods are available to detect residual surface stresses. This method may be helpful in process development as well as in spot checking of finished parts. The entire residual stress profile in the surface layer can be destructively determined by X-ray diffraction plus etch techniques or by a deflection-etch technique

8. Process Control Practices

Where process control is relied upon to maintain surface integrity, deterioration of the process control can frequently be detected by observing the change in surface finish. A gradual drift to rougher values can signal a gradual drift in process parameters. One practical rule of thumb states that if, as a corrective measure, any one of the operating parameters of a process is reset or "adjusted" by plus or minus 10 percent or more from the planned values, immediate questions should be raised as to the control status of the process. If two or more parameters are "adjusted" by 10 percent or more, the process is out of control and should be shut down until corrective action is effective.

ECONOMICS AND APPLICATIONS OF SURFACE INTEGRITY

A frequent initial reaction to surface integrity is a concern for productivity and costs The generally gentle, low speed, lower energy levels employed in machining unimpaired or enhanced surfaces do increase costs and lower production rates. However, this is only part of the overall cost picture. Consideration should be given to the added costs of defective or scrapped parts or the cost of rework or replacement during the course of manufacture when component parts fail to pass quality control inspections. Subsequent to manufacture, the costs of early product failures, complaints, liability or its insurance also must be included. Many of these costs can be ameliorated by attention to surface integrity and its contribution to product reliability and product integrity.

The more disciplined approach of surface integrity can cope with the more stringent designs that involve increasingly thinner sections of stronger materials. The principal saving can come from applying surface integrity techniques selectively Specific surface integrity specifications should not be applied all over a component part but only to the critically stressed areas. Consultation with the design engineer will frequently reveal that only a very small area, a radii, a shoulder or a section will be exposed to high

stress or severe working environment The balance of the surfaces are lightly loaded and a relaxation of specifications can be justified without compromising the product integrity

By eliminating "all-over"-type specifications and concentrating on specific critical areas. substantial cost reductions have been made Indeed. some of the "all-over" specifications have been found to be carry-over from previous generations of designers with little or no data to support the specific required levels One set of gas turbine discs of Inconel Alloy 718 had for years been specified to have a 63-microinch R_a [1 6 μm] roughness all over. When both high cycle and low cycle fatigue tests showed that the particular alloy was not sensitive to roughness level (see table 18.3-29 and figure 18.3-48). the roughness level was changed to 125 microinches R_a [3.1 μm] on all but one critical radii which was changed to 32 microinches R_a [0.8 μm]. A 7 to 12 percent reduction in machining time was effected on the six discs while increasing the quality assurance. The savings was several hundred thousand dollars per year at the then current level of production.

SELECTED SOURCES OF SURFACE INTEGRITY DATA

The following References and Bibliography provide much detailed information on specific surface integrity situations as well as general background information. Information may also be obtained on a continuing basis from the Machinability Data Center (MDC). MDC is collecting information and data on surface integrity as they become available and is evaluating the data for application to the material removal industry. These data are included in an encyclopedic collection of photomicrographs, tables and graphs of surface integrity effects from a wide variety of material and process combinations and are available to aid discussions or comparisons. Specific inquiry services are available to U. S. Government agencies and to private industry. Inquiries should be directed to Supervisor. Technical Inquiries, Machinability Data Center, 3980 Rosslyn Drive, Cincinnati. Ohio 45209; Telephone: 513-271-9510; TWX: 810-461-2840.

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SECTION 19

MACHINING GUIDELINES

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1. Good machining practice requires a *rigid setup* in addition to the selection of proper cutting speed, feed, tool material, tool geometry and cutting fluid. Rigidity in itself does not ensure a successful machining operation; however, without it, tools are subject to premature failure.

2. The machine tool must be capable of providing the rigidity required for the machining conditions used. If the size of the machine tool is not adequate or if looseness exists in the moving parts, such as spindle bearings or gibs, chatter will occur and poor tool life will result. When a rigid setup cannot be made, the feed and/or depth of cut must be reduced accordingly.

3. Excessive tool overhang is a source of trouble in a machining operation. When this condition exists, poor tool life and surface finish result, and dimensional accuracy is difficult to maintain. Stub-length drills should be used instead of jobbers-length drills where the depth of hole permits. Milling cutters should be mounted as close to the spindle as the job will allow. The length of end mills should be kept at a minimum. Climb milling usually gives better tool life and surface finish than does conventional milling if the machine tool and setup have sufficient rigidity and the feed mechanism is free from backlash.

4. Misalignment and tool runout cause other machining problems, such as oversize and bellmouthed holes when reaming and rough and torn threads when tapping and die threading.

5. Maintenance of cutting tools must be given careful consideration in the development of good machining practice. One common problem is the failure to change tools at the proper time. Tool costs become exorbitant on those jobs where tool failure is the criterion for tool change. Usually this approach results in excessive regrinding time or, in the case of a milling cutter, the replacement of broken teeth with new ones. Tooth replacement requires considerable time in addition to regrinding time.

6. When dimensional accuracy and surface integrity are not critical, high speed steel tools should be removed when the wearland on the flank of the tool reaches approximately 0.060 inch (1.5 mm) width. In the case of carbide tools, the maximum width should not be allowed to exceed 0.030 inch (0.75 mm), otherwise complete tool failure may occur. On components where dimensional accuracy and surface integrity are critical, the tool wear must be carefully limited, see section 18.3.

7. Wearland measurement is not always possible on the tool; however, it is practical to instruct the operator to change tools after a predetermined number of pieces have been machined. The number of parts to be machined per tool should be set conservatively so that the cutter will not fail. Occasionally by this procedure, a cutter may be removed before it is dull; therefore, the resharpening time will be short, but catastrophic failure will have been avoided.

8. The cutting fluid system should provide a copious flow of cutting fluid to the area where the chip is being formed. In the case of machining operations where cutting fluids are used with carbide tools, a continuous flow of the cutting fluid is imperative. Interrupted or intermittent flow can cause thermal shock and breakage of the carbide tool.

9. The concept of good machining practice involves consideration of all factors associated with the machining operation. Each detail—workpiece, fixturing, speed, feed, tool material, tool geometry, cutting fluid, and the machine tool itself—must be given careful attention to ensure success for the machining operation under consideration.

10. The *machinability* of a work material must be determined in order to select the proper machining conditions. The machinability of a material can be defined in terms of three major factors: surface integrity, tool life, and power or force requirements.

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Guidelines for Drilling 19.2

INTRODUCTION

Drills are among the most widely used tools in the shop, but their selection, grinding, and usage often receive the least care. A drilled hole is usually either a clearance hole for a fastener or a starting point for tapping, reaming, or boring. Drilling usually can be done satisfactorily with standard off-the-shelf twist drills. Where large quantities of precision holes must be produced, certain refinements in practice are necessary as follows.

- The drills should be machine ground in order to develop accurate geometry of the point.
- Point angle, web thickness, and lip clearance should be suitable for the material being drilled.
- The work should be properly supported and clamped and the drill should be guided in a drill bushing of suitable fit and length.
- Adequately powered and rigid machine tools should be utilized.

TYPES OF DRILLS

Twist Drills

A *twist drill* is an end cutting tool having one or more cutting edges and having helical and sometimes straight flutes for the passage of chips and the admission of a cutting fluid. See figure 19.2-1 and table 19.2-1 for the description and application of twist drills.

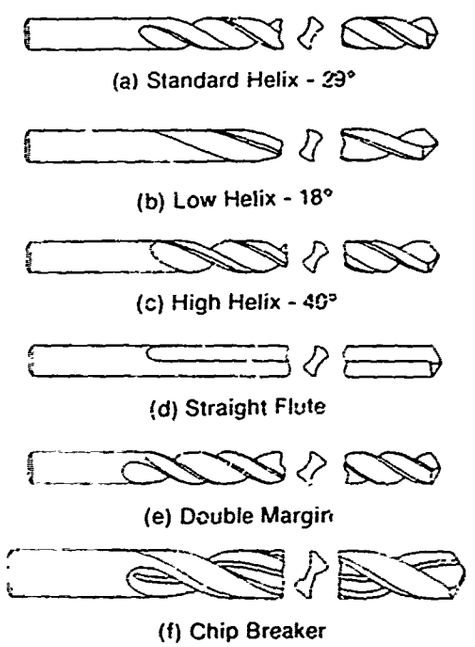


Figure 19.2-1 Twist drills.

A *standard twist drill* has two cutting edges, two helical flutes, and a straight or tapered shank.

Straight shank drills have cylindrical shanks which may be of the same or of a different diameter than the body of the drill.

Taper shank drills are preferable to the straight shank type for drilling medium and large diameter holes. The taper on the shank conforms to one of the tapers in the ANSI Standard Series. Taper shank drills generally have a driving tang and are directly fitted into tapered holes in drilling machine spindles or into driving sockets.

Double margin drills have a second pair of margins at the rear of the lands which act as steadying elements. Double margin drills may produce more accurate holes. Their size range is from 1/8 to 2 inches [3.2 to 50 mm].

Chip breaker drills have features built into the drill design to prevent long, stringy chips. They have a diameter range from 3/8 to 2 inches [9.5 to 50 mm].

Alternate Drills

When applications arise that cannot be met by using a twist drill, one of the following alternate drills can be considered:

Step Drills, figure 19.2-2
Subland Drills, figure 19.2-3
Flat Drills, figure 19.2-4
Spade Drills, figure 19.2-5
Core Drills, figure 19.2-6
Oil-Hole or Pressurized-Coolant Drills, figure 19.2-7
Gun Drills, figure 19.2-8

See tables 19.2-1 through 19.2-3 for the descriptions and applications of alternate drills.



Figure 19.2-2 Step drills.

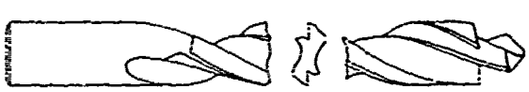


Figure 19.2-3 Subland drills.

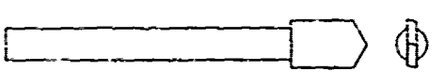


Figure 19.2-4 Flat drills.

19.2 Guidelines for Drilling

TABLE 19.2-1 Characteristics of Twist, Step and Subland Drills

	TWIST DRILLS	STEP DRILLS	SUBLAND DRILLS
Description	Twist drills are the most common. Most of these drills are made with two helical flutes which allow the removal of chips and the admission of a cutting fluid to the tip of the drill. See figure 19.2-1.	Step drills have two or more diameters produced by grinding various steps on the diameter of the drill. The steps or different diameters are ground on the same land. See figure 19.2-2.	Subland drills are combination tools having separate lands or margins which extend the full length of the flutes for each of the two or more diameters. See figure 19.2-3.
Application	Twist drills are used to produce the majority of clearance holes for fasteners and pilot holes for subsequent reaming or tapping.	Step drills produce two or more diameters in one pass of the drill, and also serve as combined drills and countersinks, combined drills and counterbores, and combined drills and reamers.	Two or more diameters can be drilled simultaneously. The different lands can be ground to permit drilling and countersinking for flathead screws or drilling and counterboring for socket head screws. Two or more diameters can be maintained constant throughout the life of the drill even after resharpening.
Tool Material	High speed steel, solid carbide, or carbide-tipped for special applications.	High speed steel	High speed steel
Size range	Standard range: 1/8 to 1-1/2 inches [3 to 35 mm] Micro range: 0.0059 to 1/8 inch [.15 to 3 mm] Large range: 1-1/2 to 6 inches [38 to 150 mm]	Standard range: 1/4 to 2 inches [6 to 50 mm]	Standard range: 5/32 to 3/4 inch [4 to 18 mm] For special sizes, the largest diameter should be no greater than twice the smallest diameter because of the variation in cutting speeds.

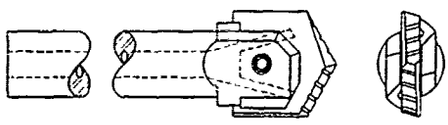


Figure 19.2-5 Spade drills.

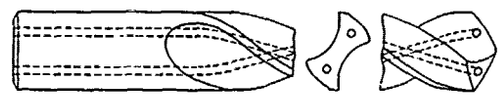
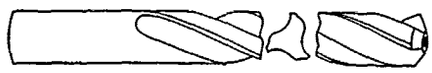


Figure 19.2-7 Oil-hole or pressurized-coolant drills.



(a) 3 Flute



(b) 4 Flute

Figure 19.2-6 Core drills.



Figure 19.2-8 Gun drills.

TABLE 19.2–2 Characteristics of Flat, Spade and Core Drills

	FLAT DRILLS	SPADE DRILLS	CORE DRILLS
Description	Flat drills derive their name from the shape of the drill body which is flat rather than the normal round configuration. The drills are produced by grinding tapered opposite flats on the drill body. The flats are usually not parallel, creating a web which is thicker at the shank. A slight back taper of 0.001 inch [0.025 mm] or less is ground on the drill body. See figure 19.2–4.	A spade drill has a removable tip or bit clamped in a special holder attached on the drill shank. See figure 19.2–5. Most holders have an axial hole through the shank to allow the passage of cutting fluid under pressure to the drill point. Replacement blades cost about 1/6 as much as a twist drill.	Core drills are multi-fluted, and have no point, similar in design to a reamer. See figure 19.2–6.
Application	Flat drills have a low production capacity, but because of their simplicity in design and low cost are occasionally used for drilling hard forgings and castings.	Spade drills smaller than 1-3/4 inch [44 mm] should be used only for shallow holes, one diameter deep vertical, two diameters deep horizontal. Do not use a center drill for starting a spade drill. Use instead a short spade drill having the same point angle as the drill to be started.	Core drills are used to enlarge cored, forged or previously drilled holes. They do not produce the original holes. Core drills are extremely rigid, and because of the greater number of flutes (3 to 6), they can be used at higher feed rates than twist drills.
Tool Material	Standard size: HSS or carbide Micro size: HSS	Blade: HSS or carbide Holder and shank: Alloy steel	High speed steel or carbide tipped
Size Range	Standard range: 3/32 to 1/2 in. [2.4 to 13 mm] Micro range: 0.001 to 3/32 inch [0.025 to 2.4 mm]	Standard range: 1 to 5 inches [25 to 125 mm] Special range: 3/4 to 1 inch [18 to 25 mm] and 5 to 15 inches [125 to 380 mm]	Standard range: 3 flute: 1/4 to 3/4 inch [6 to 18 mm] 4 flute: 1/2 to 1-1/4 inches [13 to 32 mm]

TABLE 19.2–3 Characteristics of Oil-Hole or Pressurized-Coolant and Gun Drills

	OIL-HOLE OR PRESSURIZED-COOLANT DRILLS	GUN DRILLS
Description	An oil-hole drill is either a twist drill or a straight fluted drill which has one or more continuous holes through its body and shank to permit the passage of cutting fluid under pressure. The holes can be through either the lands or the web of the drill. See figure 19.2–7. Chip-breaking grooves are sometimes ground in the drill point to break and curl the chips to aid ejection.	A gun drill is a special straight flute drill for producing deep holes. It has a straight fluted tip, cutting to center, mounted in a tubing shank. The tips are often brazed to the shanks, but in the larger sizes, the tips are keyed or pinned to the shanks for convenience in removal for regrinding. Both the tip and the shank allow for ample volume of coolant under high pressure to reach the cutting edges and also to wash away the chips. See figure 19.2–8.
Application	Oil-hole drills are very suitable for making deep holes where flood applications of a cutting fluid would be ineffective. Increased metal removal rates are possible in both normal and deep holes by using oil-hole drills instead of flood cooling. Both constant pressure and pulsating pressures from 50 to 300 psi [345 to 2068 kPa] are employed.	Gun drills are used for making very deep holes that require extremely close tolerance in straightness and diameter.
Tool Material	High speed steel or carbide-tipped steel for special applications.	The tip is usually carbide, and the shank is alloy steel tubing.
Size Range	Standard range: 5/32 to 1-1/2 inches [4 to 38 mm]	Standard range: 1/8 to 2 inches [3 to 50 mm]

19.2 Guidelines for Drilling

DRILL GEOMETRY

Drill Point

Point Angle
Standard drills have point angles of 118 degrees. The point angle may be increased up to 150 degrees for very hard or tough materials. For softer materials such as aluminum or copper alloys, the point angle may be 90 to 100 degrees.

Double Point Angle
When drilling very hard or abrasive materials, double angles are sometimes ground on the point to reduce chipping of the corners of the lips. This is done by first grinding the larger included angle (118 to 140 degrees) and then regrinding the smaller included angle (60 to 90 degrees) on the corners, giving the effect of a chamfer at the corner.

Thinned Web
The central web of the drill increases in thickness toward the shank. Hence, the point must be thinned as the drill is ground back so as to prevent excessive end pressure. This is usually required when the web thickness exceeds one-fifth of the drill diameter. Techniques used to reduce the web thickness include the undercut thinned point, the notched point, and the crankshaft point.

Radius Corner
A radial lip twist drill has curved outer lips. These curves allow stress to be uniformly distributed over the entire cutting area. This design may produce a smoother finish in the hole and may reduce the burrs at breakthrough. This point can be produced on a special machine designed for that purpose or on general-purpose cutter grinding machines.

Spiral Point
Reducing the point from a regular chisel edge to a spiral point gives the drill a better self-centering effect. The spiral point must be ground on a spiral-point-grinding machine.

Multiple Point and Relief Angle
Drills having points with more than one included angle and more than one angle of relief (faceted) can be self-centering and chip-breaking for use in hard materials.

Helix Angle

Standard Helix
A standard helix (approximately 29 degrees) high speed steel drill is used for drilling most cast irons and steels. See figure 19.2-1 (a).

Low Helix
Low helix drills (approximately 18 degrees) have reduced axial rakes which facilitate the penetration of brass, plastics, and other soft materials. See figure 19.2-1 (b).

High Helix
High helix drills are made with wide flutes and narrow lands, for drilling deep holes in mild ferrous and nonferrous materials. The higher helix (approximately 40 degrees) removes chips more effectively. See figure 19.2-1 (c).

Straight Flute
Straight flute drills (zero helix) are especially adapted for drilling brass and other soft or very hard metals. See figure 19.2-1 (d).

Lip Clearance
For most drilling, the lip clearance varies from 7 to 25 degrees depending on the drill size. Smaller drills require more clearance, while larger drills require less. In general, for harder materials, the clearance should be as small as possible to allow maximum strength to the cutting edge.

HOLE SIZES

Micro Drilling
For holes from 0.001- to 0.020-inch [0.025 to 0.5 mm] diameter, flat drills are used over this entire size range. Twist drills are used for hole sizes over 0.006 inch [0.15 mm]. Speeds must be much lower and feed rates higher than are used for larger drills so as not to produce a powder that will pack in the flutes.

Normal Drilling
For holes from 0.014- to 3-inch [0.35 to 75 mm] diameter, standard twist drills are generally used.

Large Holes
For holes larger than 3 inches [75 mm] in diameter, spade drills, gun drills, or trepanning tools are needed.

Deep Holes
When drilling deep holes with twist drills, the recommended speeds and feeds should be reduced as the holes become deeper, as shown in table 19.2-4. The drill should also be retracted periodically to clear the chips and lubricate the points.

TABLE 19.2-4 Reduction of Speed and Feed for Drilling Deep Holes with Twist Drills

HOLE DEPTH drill diameters	REDUCE SPEED BY	REDUCE FEED BY
3	10%	10%
4	20%	10%
5	30%	20%
6	35%	20%
8	40%	20%

Oil-hole drills are helpful in deep-hole drilling. Hole depths up to 30 diameters are sometimes possible. The feed rate should be reduced as the holes become deeper, as shown in table 19.2-5.

TABLE 19.2–5 Reduction of Feed for Deep-Hole Drilling with Oil-Hole Drills

HOLE DEPTH drill diameters	REDUCE FEED BY
5 to 7	10%
8 to 10	20%
over 10	30%

ACCURACY OF DRILLED HOLES

Accuracy of Holes Drilled with Twist Drills

There are two elements of hole accuracy—location and oversize. Table 19.2–6 indicates the accuracy of holes drilled with twist drills with and without center-drilled holes and drill bushings. Holes drilled without center-drilled holes and drill bushings tend to be bellmouthed.

Effect of Drill Point

The point angle affects hole location and size. Point angles which are more acute than standard point angles (smaller included angle) have more of a self-centering effect on the drill. The blunter the point angle, the greater the care and skill which must be exercised to control hole location and size. Special point grinds, such as spiral points, also improve the centering effect of the drill.

Point Grinding Faults

Cutting lips of nonuniform length or angles will produce oversize holes and excessive margin wear. Insufficient clearance will result in excessive drill thrust and will produce excessive heating and burning of the work material and drill point. A too large lip clearance, leaving insufficient support behind the cutting edges, results in chipping and crumbling of the cutting edges.

Hole Location

The machine tool and the setup affect the accuracy of the location of the hole. Approximate placement capabilities for three general categories of machining with respect to true location are as follows:

Jig borer	±0.0002 inch [±0.005 mm]
NC drill	±0.0025 inch [±0.064 mm]
Drill press (with bushings in drill jig)	±0.002 inch [±0.05 mm]
Drill press without bushing	±0.015 inch [±0.08 mm]

TOOL MATERIALS FOR DRILLS

High Speed Steel

Several common grades such as M1, M7 and M10 [S2 and S3] are used in the majority of drilling operations. See section 14.2 for complete listing of HSS compositions.

Cobalt High Speed Steel

Grades containing combinations of high cobalt with high vanadium or high carbon such as T15, M33, and M41 through M47 [S9, S11 and S12] are very useful in drilling hard steels, titanium alloys and nickel-base alloys. The cobalt grades usually give higher tool life or faster production than regular high speed steel. The cobalt grades are more expensive and in some cases are more difficult to grind than the common high speed steels.

Surface Treated HSS Drills

Various surface treatments such as cyaniding and nitriding can be applied to high speed steel drills to increase the hardness of the outer layer of materials. Cyanided and nitrided HSS drills are considered when drilling hard and abrasive materials which allow very short tool life of untreated HSS drills. Flash chrome plating is used on occasion when drilling small-diameter holes in printed circuit boards, carbon and graphite, and some nonferrous metals. Other treatments such as special polishing and black oxiding are used to minimize friction between the drill and the workpiece, galling of chips in the flutes, and excessive work material buildup on the drill lips.

TABLE 19.2–6 Average Accuracy of Holes Drilled with Twist Drills

CONDITION	DIAMETER					
	1/8 to 1/4 inch		1/4 to 3/4 inch		3/4 to 1-1/2 inch	
	Oversize	Location	Oversize	Location	Oversize	Location
No center drilled hole—no bushing	0.003	±0.007	0.006	±0.008	0.008	±0.009
Center drilled hole—no bushing	0.003	±0.004	0.003	±0.004	0.004	±0.005
Drill bushing	0.002	±0.002	0.003	±0.002	0.004	±0.003
No center drilled hole—no bushing						
Center drilled hole—no bushing						
Drill bushing						

19.2 Guidelines for Drilling

Carbide Drills

Twist or straight-flute drills can be tipped with carbide cutting edges or be made of solid tungsten carbide.

- Carbide-tipped drills are usually preferred because they are less expensive than solid carbide drills. Standard carbide-tipped drill diameter range is usually from 3/32 to 1-1/2 inches [2.4 to 38 mm].
- Solid carbide drill diameter range is from 1/16 to 1/2 inch [1.6 to 13 mm] (or No. 80 to No. 13).
- Applications for carbide drilling:
  a. For steels harder than 50 R_C to avoid surface damage to the steel
  b. High production drilling on cast iron and aluminum
  c. Drilling of reinforced plastics including circuit boards

COOLANT SYSTEMS FOR DRILLING

Flood

The most commonly used method of applying coolant to the drill is the overhead flood, where a constant stream of liquid is directed at the hole.

Mist

Application of a mist of coolant to the drill is very useful in situations where a recirculating coolant system would be impractical or impossible, such as on large sheets or airframes.

Oil-Hole or Pressurized-Coolant Drilling System

This application is used often in screw machines and turret lathes for drilling deep holes. The coolant is pumped under constant or pulsating pressure (see section 3.3).

Recent availability of relatively inexpensive pump and rotating seal equipment will permit the use of oil-hole drills in almost any drill press, old or new, provided that it is in reasonably good condition. Oil-hole or coolant-fed HSS drills are now available in a wide range of sizes in both high speed steel and carbide-tipped styles. Oil-hole usage may, in many cases, result in increased metal removal rates over flood cooling for normal depth holes as well as for deep holes.

THIN SHEET DRILLING

Very thin sheets, either metallic or nonmetallic, should be backed up with a solid block of wood or soft steel to prevent cracking in brittle materials, deformation in metals, or oversize holes. The formation of burrs, both at the entrance and the exit of the drill, is a common occurrence in drilling "sandwich" layers of sheets, and delamination of pressed and sintered alloys may occur under heavy feeds. The use of a backup minimizes both burring and delamination. Burrs and delamination can also be minimized by controlling the operation to ensure that drills are sharp at all times.

Very large assemblies of sheet material, usually aluminum, titanium or steel alloys, are frequently drilled in the aircraft industry. The larger assembly size usually dictates the use of portable drilling equipment. This equipment may be electric- or pneumatic-powered. The drills may be hand-fed when drilling aluminum alloys, but are power-fed when drilling titanium alloys or steel.

DRILLING NONMETALLICS

Plastics

Use low helix drills with deep-polished, large-radius flutes to facilitate chip removal. Point angles should be 60 to 90 degrees; use 60 degrees on sheet plastics.

Some plastics produce undersize holes. To overcome this problem, use drills 0.002- to 0.003-inch [0.05 to 0.08 mm] oversize. Before using a cutting fluid, check the possible damaging reaction to the plastic; or use an air-cooling jet.

Composites

Composite materials containing glass, graphite, boron and Kevlar fibers are finding increasing applications in aerospace, automotive, marine and commercial items. Basically, these materials are composed of high-strength fibers impregnated in a plastic matrix. These materials are very hard and abrasive by nature; therefore, conventional drills made of both high speed steel and carbide find limited usage because their tool life is short and they tend to delaminate the material on exiting the drilled hole.

These problems have practically eliminated the use of HSS drills and have led to the development of a family of new drill configurations and drilling technology utilizing both carbide and diamond. According to present technology, the drilling of small-diameter holes, up to 3/16-inch [4.75 mm] diameter, is best performed using solid carbide drills having a low flute helix and a smaller than normal included point angle. These drills have less tendency to delaminate the material when a back-up material is impractical to use.

For larger diameter holes, industry has turned to a widespread use of diamond-impregnated core drills. These drills have brought vast improvements in hole quality, hole size and drill life. Running at much higher speeds than conventional drilling speeds, diamond core drills grind the hard fibers, thus eliminating fiber whiskers in the hole.

A new development in the use of diamond-impregnated core drills employs ultrasonic vibration to produce faster penetration rates. However used, diamond core drills do have a tendency to delaminate upon exiting the hole; therefore, it is recommended that wherever possible the underside of the hole be backed up with wood, aluminum or plastic. A newer family of composites composed of fibers in a metal matrix, such as aluminum, are posing problems in drilling which require additional process developments, such as utilizing rotary ultrasonic core drilling, electrolytic diamond drilling and lasers to produce acceptable holes.

Tool Life 19.3

Tool life is one of the most important factors in the evaluation of machinability. Specifically, the manufacturing engineer needs to know the relation of tool life to speeds, feeds and the other pertinent machining parameters. For production operations, tool life is usually expressed as the number of pieces machined per tool grind. In machinability testing, tool life is generally defined as the cutting time in minutes to produce a given wearland for a set of machining conditions. This cutting time can be converted to cubic inches of metal removed for a given depth of cut.

Turning tests usually are used for evaluating the machinability of a material in terms of tool life. This operation is used because of the simplicity of the cutting tool. In addition, all of the machining conditions, such as speed, feed, tool geometry, tool material, and cutting fluid, can be readily controlled. By varying one of the machining conditions and keeping the others constant, it is possible to determine the effect of such a change on tool life. The relationships among the various machining variables are obtained in this manner.

In a machining test such as turning, the tool is removed after a given amount of wear is produced on the flank of the tool. The wearland is usually 0.015 or 0.030 inch [0.38 or 0.75 mm] for carbide and 0.060 inch [1.5 mm] for high speed steel. It is general practice in these tests to stop the machining at frequent intervals and examine the wearland on the tool. The time to produce the wearland is then recorded. A typical data sheet for turning tests is shown in figure 19.3-1. This procedure is continued until the wearland reaches a predetermined width, which in these tests was 0.015 inch [0.38 mm]. It should be noted that intermittently measured tool wear rates may not fully indicate rates of continuous cutting wear. Hence, wear tests should be run both ways.

Initially, a tool life curve is obtained with several different speeds, keeping the other variables constant, thus obtaining a relationship between cutting speed and tool life. The recommended cutting speed for a high speed steel tool is generally the one which produces a 60-minute tool life. With carbide, the tool life can be much shorter, particularly if a throwaway-type tool blank is used. In this case, a 30-minute tool life may be satisfactory. When a tool life curve is available for a range of cutting speeds, the tool engineer can select the cutting speed which will give him the best compromise between tool life and production rate. Tool life curves for various feeds which show the effect of cutting speed are presented in figures 19.3-2 and 19.3-3. Figure 19.3-2 shows that for tests on 8640 steel using a carbide tool, the longest tool life was obtained at 300 feet per minute [90 m/min] with a feed per revolution of 0.010 inch [0.25 mm]. Figure 19.3-3 shows the tool life in cubic inches of metal removed for the same test conditions. In this case, the greatest tool life was obtained at 300 feet per minute [90 m/min] with a feed per revolution of 0.020 inch [0.5 mm], even though the tool life in minutes was less than that obtained when using a feed per revolution of 0.010 inch [0.25 mm].

Once the tool life curves have been established showing the effect of cutting speed, other tests can be run to develop the relationships between tool life and other machining variables. Tool life curves on the effect of feed for a constant cutting speed are shown in figures 19.3-4 and 19.3-5. Tool life versus feed is given for three different cutting speeds. The curves in figure 19.3-4 show tool life in minutes. The longest tool life was obtained using a feed per revolution of 0.010 inch [0.25 mm] with a cutting speed of 300 feet per minute [90 m/min]. Figure 19.3-5 shows tool life in cubic inches of metal removed. At a cutting speed of 300 feet per minute [90 m/min], tool life was greatest when using a feed per revolution of 0.020 inch [0.5 mm]. For complete results, a three-dimensional graph of speed and feed versus tool life is necessary.

Other tool life tests can be performed to evaluate the effect of the other machining variables, such as carbide grade, tool geometry, and cutting fluid. Figure 19.3-6 shows a set of tool life curves comparing the effect of a carbide grade on tool life. Tool life curves for various materials can be grouped on the same chart to compare the relative machinability of each of the materials when machined under similar conditions. A group of tool life curves for turning various materials is shown in figure 19.3-7.

This presentation on tool life curves has dealt mainly with turning tests. While turning tests are most widely used, it is preferable whenever possible to test using the particular machining operation in question, such as turning, milling, drilling, reaming, tapping, etc. The tool life curve is a valuable source of machining information; from it the tool engineer, designer, or planner can obtain machining conditions which will produce maximum production at a minimum cost for the machining operation. A further discussion of cost is presented in section 21.

PROJECT NUMBER: 18C | TEST NUMBER: 11 | MACHINABILITY TEST DATA SHEET | OBSERVED BY: HWH | DATE: 5/15/59

MATERIAL: 8640 STEEL

HEAT TREATMENT: NORMALIZED | MICROSTRUCTURE: 75% PEARLITE, 25% FERRITE

HARDNESS: 190 - 192 BHN

MACHINE: AMERICAN PACEMAKER

TOOL: CARBIDE | MATERIAL: C-6

BACK RAKE 0° | RESULTANT RAKE — | NOSE RADIUS .040"

SIDE RAKE 6° | INCLINATION — | CHIP BREAKER —

SCEA 0° | SIDE RELIEF 5°

ECEA 5° | END RELIEF 5°

CUTTING FLUID: DRY

BAR No.	SPEED fpm	BAR Dia. in.	rpm	DEPTH of CUT, in.	FEED in./rev.	TOOL WEAR, in. uniform	TOOL WEAR, in. localized	TIME min.	POWER kw. input	SURFACE FINISH, in	METAL REMOVED cu. in.	METAL REMOVED per in. edge
S-3	600	3.910	587	.100	.010	.003	—	2'40"				
(192)		3.510	654			.009	—	7'42"				
		3.310	694			.013	.014	9'55"				
		3.110	739			.015	.017	11'				
S-3	300	3.110	310	.100	.010	.001	—	2'10"				
		2.510	458			.003	—	13'16"				
		2.110	545			.004	—	19'20"				
S-5	300	3.800	301			.006	—	24'38"				
(190)		3.400	337			.010	.011	34'24"				
		3.200	358			.012	.0125	38'50"				
		3.000	382			.013	.014	41'				
		2.800	408			.0145	.015	43'				
		2.800	408			.0155	.016	44'				
S-5	400	2.800	527	.100	.010	.002	—	2'13"				
		2.200	694			.007	—	9'48"				
		2.000	763			.008	—	11'55"				
S-6		3.970	385			.010	—	16'				
(190)		3.570	428			.013	.014	23'44"				
		3.370	453			.0145	.016	26'				
		3.370	453			.015	.0165	27'				

Figure 19.3–1 Typical data sheet for turning tests.

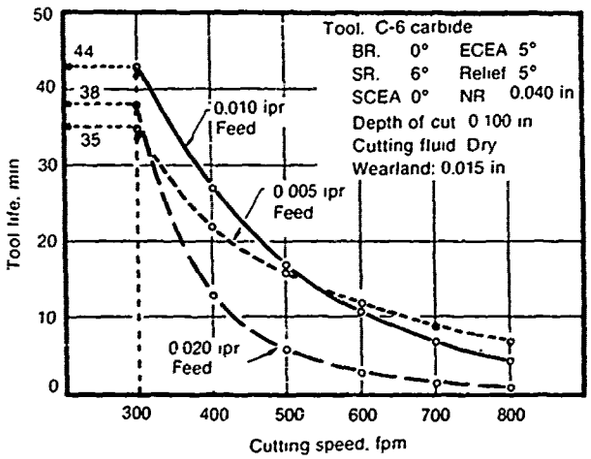


Figure 19.3–2 Effect of cutting speed on tool life for turning 8640 steel, 190 Bhn.

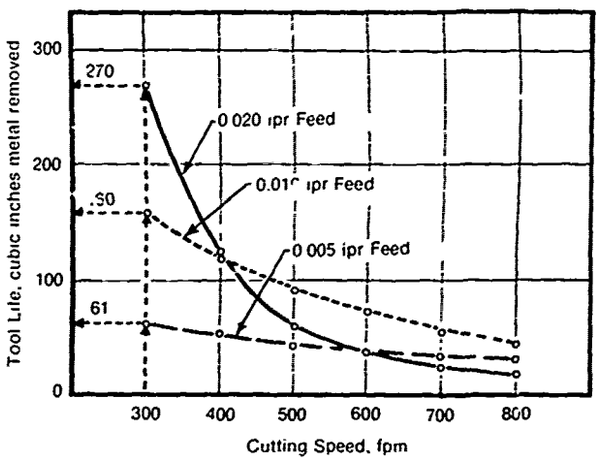


Figure 19.3–3 Effect of cutting speed on tool life for turning 8640 steel, 190 Bhn. See figure 19.3–2 for test conditions.

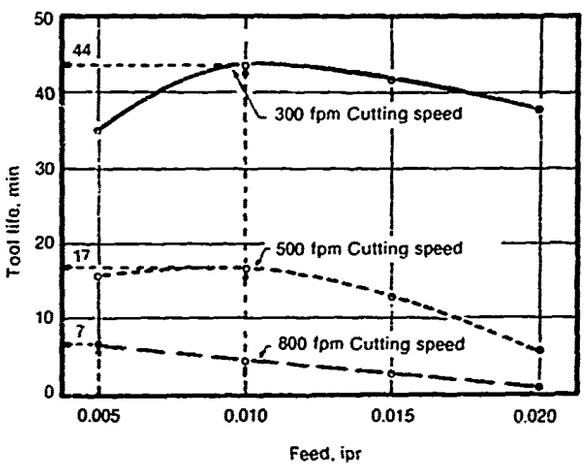


Figure 19.3–4 Effect of feed on tool life for turning 8640 steel, 190 Bhn. See figure 19.3–2 for test conditions.

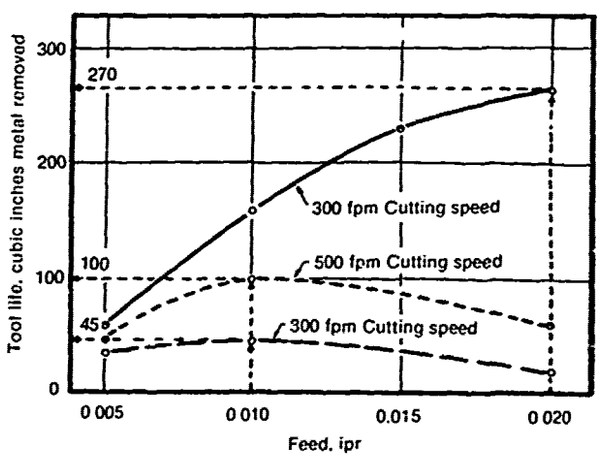


Figure 19.3–5 Effect of feed on tool life for turning 8640 steel, 190 Bhn. See figure 19.3–2 for test conditions.

19.3 Tool Life

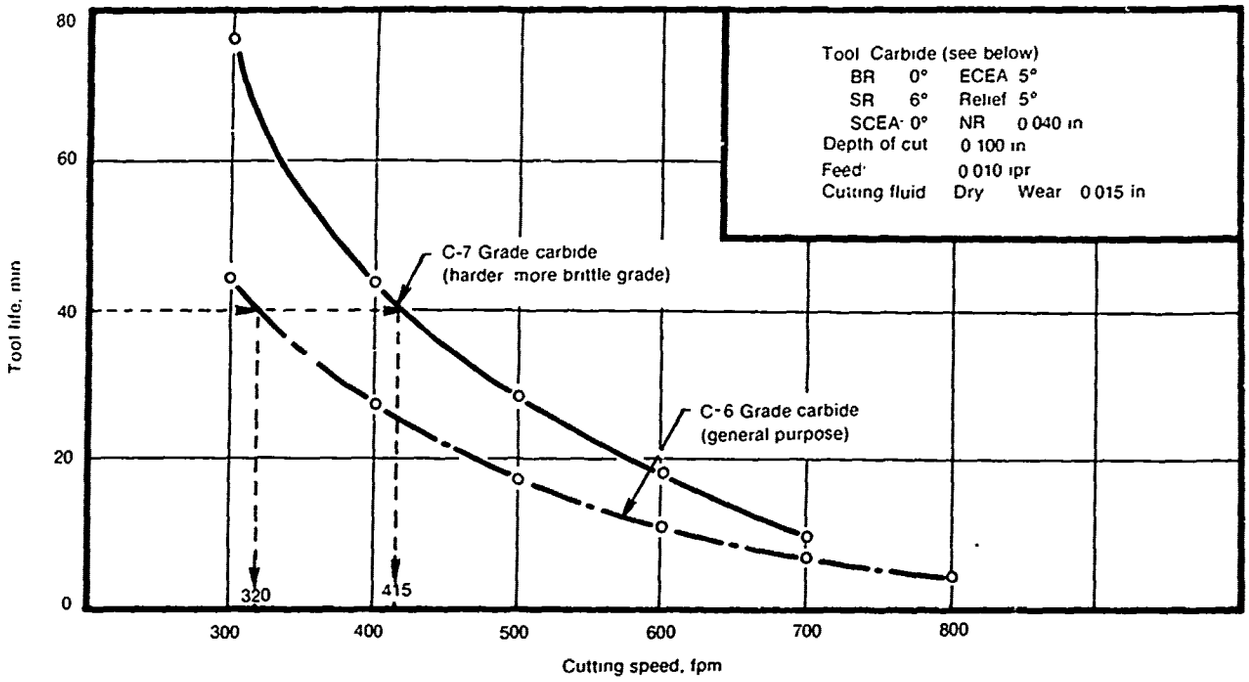


Figure 19.3–6 Effect of carbide grade on tool life for turning 8640 steel, 190 Bhn. Best tool life was obtained at 300 fpm using C-7 grade carbide. For a 40-minute tool life, AISI 8640 steel can be turned at 415 fpm using C-7 grade carbide, compared to 320 fpm with C-6 grade carbide.

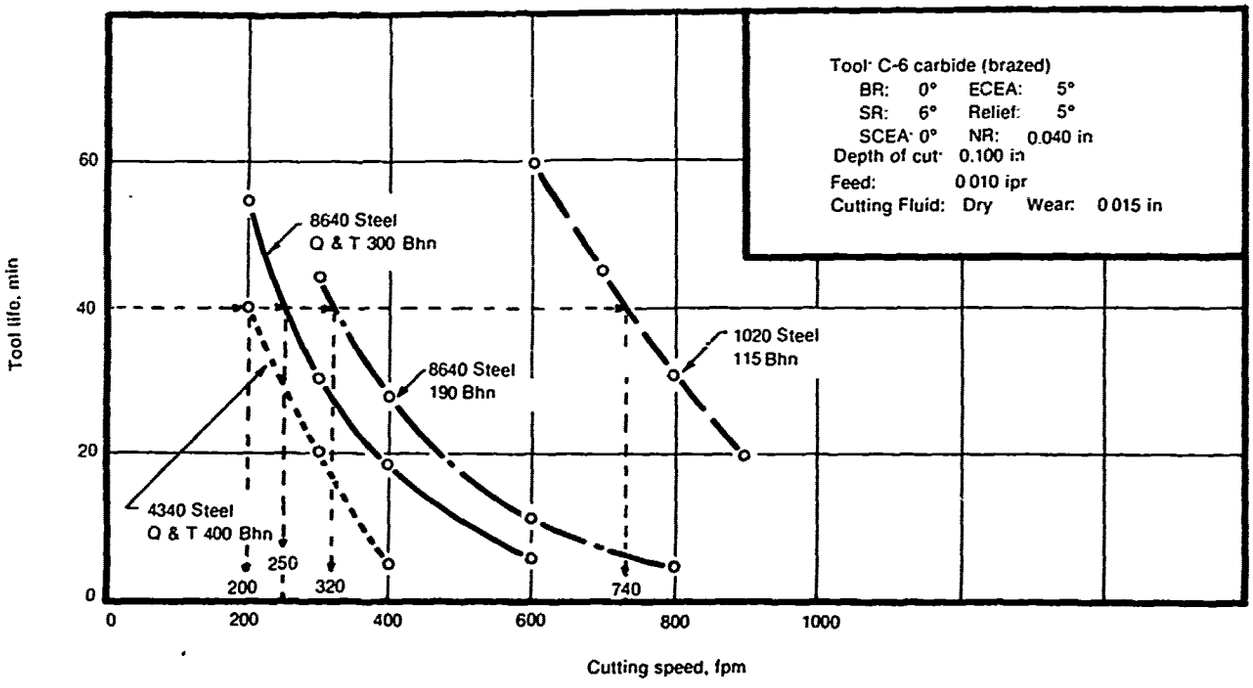


Figure 19.3–7 Effect of cutting speed on tool life for turning various materials. For a 40-minute tool life turn the above steels at: 740 fpm for 1020 steel, 115 Bhn; 320 fpm for 8640 steel, 190 Bhn; 250 fpm for 8640 steel, quenched and tempered to 300 Bhn; and 200 fpm for 4340 steel, quenched and tempered to 400 Bhn.

There are various degrees of sophistication of machinability data available for use by industry. A general discussion of the types of data will be given.

Tables of Recommended Machining Conditions

This *Machining Data Handbook* contains the practical starting conditions for most of the significant work materials and machining operations. It supplies the recommended feed, speed, tool material, tool geometry, and cutting fluid as well as data for determining horsepower requirements for various machining operations. It also contains the most practical and readily accessible data for general shop application.

Wide Range Machining Data

Detailed machining data covering the tool life obtained under a wide range of machining parameters such as speed, feed, tool material, tool geometry, and cutting fluids are often useful in selecting a set of conditions for machining at lower costs or higher production rates. The detailed machining parameters can be obtained from laboratory studies or from shop studies by varying the pertinent parameters and observing their effect on tool life. Data formats for presentation of wide range machining data are shown in section 21.

Cost and Production Rate Determination and Analysis

It is possible and desirable to calculate the total cost and production rate on any machining operation. Section 21 supplies the necessary procedures for making these calculations based on the relation of tool life to the machining parameters.

Mathematical Correlation of Machining Parameters with Tool Life and Subsequent Optimization of Cost and Production Rates

Attempts have been and are being made to correlate tool life with the other pertinent machining parameters. The usual approach is to obtain empirical data relating tool life to speed, feed, and depth and width of cut. In some cases, these data can be put into the fairly simplified equation:

$$vT^n f^a d^b w^c = K$$

where: v = cutting speed
T = tool life
f = feed
d = depth
w = width

and n, a, b, c, and K are constants.

Unfortunately, it has been found that most work materials when machined by the various operations do not follow this simple relationship except for restricted regions of cutting speeds and feeds. Despite this, certain combinations of work materials and operations that obey this simple law permit one to obtain this mathematical relationship between tool life and the various machining parameters. For these situations, it is possible to calculate the machining conditions which provide minimum cost or maximum production rate or maximum profit. Whenever such calculations are made, it is wise to verify the calculation by shop trial.

Machinability Ratings

There appears to be an endless desire to provide macninability ratings for materials. The original machinability rating index was based upon turning B1112 steel at 180 feet per minute [55 m/min] with a high speed steel tool for an index of 100 percent. This index was developed years ago under strong influence from the Independent Research Committee on Cutting Fluids.

Since that time, high speed steels have lost ground to carbides in turning. It is tempting to try to use a single numerical value to designate the degree of difficulty (or ease) with which a particular material can be machined. Unfortunately, it has been found that this machinability rating of a given work material changes with the type of operation involved and with the tool material selected. The inconsistencies and futility of applying machinability ratings can be seen in table 19.4-1.

Machinability ratings are given for four work materials and three operations—turning, milling and drilling. In addition, the rating is given for both high speed steel and carbides for the turning and milling. In machining 4340 steel, the rating is seen to vary from 25 to 88 depending upon the operation and tool material.

TABLE 19.4-1 Machinability Index Inconsistencies

OPERATION	WORK MATERIAL			
	4340 Steel 340 Bhn	Ti-3Al-13V-11Cr 285 Bhn	17-7 PH Steel 170 Bhn	250 Maraging Steel 330 Bhn
Turning				
HSS	25	—	32	54
Carbide	31	16	18	59
Milling				
HSS	25	16	37	74
Carbide	88	20	53	83
Drilling				
HSS	42	17	42	92

The application of the machinability index should be restricted to very special situations where the ratings have meaningful and consistent values. Another application of the machinability rating system involves the use of relative machining time, an example of which is given. A more precise and logical approach to the selection of machining data is to use the data contained in the *Machining Data Handbook*.

SECTION 20

GRINDING AND ABRASIVE MACHINING

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CONVENTIONAL WHEELS

Wheel Identification

Table 20.1-1 shows the standard marking system for identifying grinding wheels and other bonded abrasives (per ANSI B74.13-1977 and ISO 525-1975E).

Tables 20.1-2 and 20.1-3 list the codes that are used by the various grinding wheel manufacturers for aluminum oxide wheels and silicon carbide wheels, respectively.

Abrasive Types

The two most common abrasives used in industrial applications are aluminum oxide and silicon carbide. Aluminum oxide is a synthetic material produced in an electric furnace. Aluminum oxide abrasives have a wide variety of properties, such as toughness and friability, which can be tailored to specific job requirements. Tough aluminum oxide is used for rough grinding operations. Semifriable aluminum oxide is a general-purpose type. White friable aluminum oxide is used for tool grinding and for heat sensitive materials, while pink friable aluminum oxide is used for difficult-to-grind alloys.

Silicon carbide, also a product of the electric furnace, is harder than aluminum oxide and is used primarily for grinding nonmetallic, nonferrous and low-tensile-strength materials. Green friable silicon carbide is used for general-purpose grinding of tungsten carbide. Various combinations of aluminum oxide and silicon carbide abrasives are available only in organic bonds—resinoid, rubber and shellac.

Grain Size

Grain size influences surface roughness, stock removal rate, chip size and corner holding ability. Surface roughness depends on a number of factors, such as wheel hardness, structure and dressing methods, but finer-grain abrasives tend to produce surfaces with lower roughness values.

Wheel Grade

The grade or hardness of a wheel is a measure of the strength of the bond holding the grains in the wheel. The major factor affecting bond strength is the amount of bond holding an individual grain. Wheel grades range from A to Z in order of increasing bond content.

Wheel grade requirements vary inversely with the workpiece hardness. Harder materials require softer-grade wheels, while softer materials require harder-grade wheels.

Wheel Structure

The wheel structure number indicates the porosity or density of the wheel. Low numbers indicate a dense structure, while high numbers indicate an open structure.

Wheels having an open structure are recommended for surface grinding, while wheels having a dense structure are recommended for cylindrical, centerless and form grinding. Dense wheel structures are recommended when low surface roughness values are required.

Bond

Of the several bond types listed in table 20.1-1, resinoid, rubber and vitrified are the most widely used types.

Vitrified bonds are more brittle than resinoid bonds but are superior for holding form. Normal speeds for vitrified wheels are 6,500 or 8,500 feet per minute [33 or 43 m/s]. Higher speeds of 10,000 to 16,500 feet per minute [51 to 64 m/s] require special wheels, tested and approved for the particular speed and machine.

Normal speeds for resinoid-bond wheels range from 6,500 to 9,500 feet per minute [33 to 48 m/s] depending on the actual grading. In some cases, cutoff wheels and snagging wheels can be run at speeds up to 16,500 feet per minute [64 m/s]. In any case, the speed marked on the blotter is the maximum permissible speed. Resinoid-bond wheels are used for wet grinding and for cutoff operations.

Truing and Dressing

Before truing a grinding wheel, the spindle should be run until it is up to operating temperature. Then the diamond truing tool should be placed at the center of the wheel and fed out to the wheel edge, and then from edge to edge. A copious flow of coolant should be directed at the wheel-tool interface.

The face of the wheel must be prepared for the job it is expected to do by dressing. When dressing wheels for finishing operations, the diamond tool is fed slowly across the face; when dressing wheels for roughing operations, the diamond tool is fed more rapidly.

TABLE 20.1–1 Markings for Identifying Grinding Wheels and Other Bonded Abrasives
(Standard marking system chart per ANSI B74.13-1977 and ISO 525-1975E)

51	A	36	L	5	V	23

PREFIX	ABRASIVE TYPE	ABRASIVE (GRAIN) SIZE				GRADE			STRUCTURE		BOND TYPE*	MANUFACTURER'S RECORD
		Coarse	Medium	Fine	Very Fine	Soft	Medium	Hard	Dense to Open			
Manufacturer's symbol indicating exact kind of abrasive *(use optional)*	A - Aluminum Oxide C - Silicon Carbide	8 10 12 14 16 20 24	30 36 46 54 60	70 80 90 100 120 150 180	220 240 280 320 400 500 600	A E B F C G D H	I M J N K O L P	Q V R W S X T Y U Z	1 9 2 10 3 11 4 12 5 13 6 14 7 15 8 16 etc. *(use optional)*		B - Resinoid BF - Resinoid Reinforced E - Shellac O - Oxychloride R - Rubber RF - Rubber Reinforced S - Silicate V - Vitrified Mg - Magnesia	Manufacturer's private marking to identify wheel *(use optional)*

*ISO 525-1975(E) specifies a Mg-Magnesia bond not contained in ANSI B74.13-1977 and does not include bond types O-Oxychloride and S-Silicate.

TABLE 20.1–2 Comparative Aluminum Oxide Wheel Marking Symbols
(Includes both manufacturers' prefixes and abrasive symbols)

MANUFACTURER	HEAVY DUTY			REGULAR	SEMI-FRIABLE	FRIABLE	MIXTURE OF ALUMINUM OXIDE	MIXTURE OF Al. Ox. & SiC
	Aluminum Oxide	Zirconia	Sintered					
Acme	A	3XT	7XT	A	FA	—	WA	CA
	—	8XT	—	RA	—	—	—	C1A
	—	—	—	—	—	—	—	C2A
Bancroft	NA	ZA	VA	A	1A	2A	5A	7A
Bay State	—	—	1A	A	3A	9A	8A	CA
	RA	—	15A	—	—	—	2A	MA
	—	27A	25A	—	—	17A	—	GA
	—	33A	—	—	—	—	16A	—
Bendix	RA	—	KA	A	FA	WA	GA	CA
	—	—	6A	—	BA	—	EA	—
	—	31A	JA	—	—	—	DA	—
	—	2A	22A	A	35	48	15	CA
	—	—	88A	—	29	—	18	—
	—	—	—	—	--	—	115A	—
	—	—	—	A	—	—	FBA	AC
	—	—	—	—	—	—	FWA	—
	—	—	—	—	—	—	BWA	—
Blanchard	—	—	—	A	5A	9A	59A	CA
	—	—	—	—	6A	—	91A	—
Brightboy	—	—	—	ALO	—	—	—	—
	—	—	—	F	—	—	—	—
Buckeye	A	ZA	SA	A	FA	WA	MA	CA
Bullard	3A	—	A	FA	WA	6A	6TA	CA
Carborundum	A	VA	WA	A	BA	AA	DA	CA
	—	XA	—	—	GA	—	BGA	—
	—	—	—	—	PA	—	FA	—
	—	—	—	—	SA	—	—	—
Chicago	TA	ZA	—	51A	12A	53A	50A	CA
	—	ZX	—	—	52A	—	54A	—
	—	AZ	—	—	55A	—	—	—
Cincinnati	—	—	—	A	2A	9A	97A	CA
	—	—	—	—	4A	—	—	C2A
	—	—	—	—	—	12A	—	C4A
	—	—	—	—	—	—	—	C12A
Colonial	HA	—	—	A	TA	20A	—	5TAC
	—	—	—	—	—	21A	—	10TAC
	—	—	—	—	—	22A	—	5CTA
	—	—	—	—	—	25A	—	10CTA
	—	—	—	—	—	24A	5TA	—
	—	—	—	—	—	26A	10TA	—
	—	—	—	—	—	—	15TA	—
de Sanno	A	XA	—	A	7A	9A	97A	CA
	—	YA	—	AT	7AT	10A	JA	DA
	—	ZA	—	—	8A	RA	7RA	FA
	—	—	—	—	—	12A	4A	—
	—	XZ	—	—	—	—	KA	GA
	—	—	—	—	—	—	KTA	HA
	—	—	—	—	—	—	SA	—
	—	—	—	—	—	—	PTA	—
Edmar	HA	ZA	SA	A	FA	WA	MA	CA
Ferro (FMR Electro)	TA	ZT	EA	A	FA	13A	2A	BA
	YA	BZT	XA	—	JA	36A	15A	CA
	—	CZT	—	—	TFA	WA	HA	DA
	—	—	—	—	—	—	LA	—
Fisher	M	ZR	—	—	A	B	AB	AC

SOURCE: Grinding Wheel Institute.

TABLE 20.1-2--Continued

MANUFACTURER	HEAVY DUTY			REGULAR	SEMI-FRIABLE	FRIABLE	MIXTURE OF ALUMINUM OXIDE	MIXTURE OF Al. Ox. & SIC
	Aluminum Oxide	Zirconia	Sintered					
Gardner	–	–	–	A	82A	80A	81A	AC
	–	–	–	84A	–	–	83A	–
	–	–	–	87A	–	-	85A	–
	–	–	–	–	–	–	86A	–
	–	–	–	–	–	–	88A	–
	–	–	–	–	–	–	91A	–
Grier	–	–	–	A	27A	28A	78A	CA
	–	–	–	–	–	22A	–	–
	–	–	–	–	–	29A	–	–
Hanson	TA	ZA	MA	–	BA	RA	HA	CA
	–	–	–	–	FA	WA	W2A	AC
ITT Abrasive	HA	XA	MA	A	KA	WA	ZA	JA
	–	–	–	–	PA	–	EA	–
Jowitt & Rodgers	–	–	–	G	B	W	BW	BX
MWA	5A	54A	63A	1A	8A	2A	SFA	8AC
	–	–	–	–	11A	–	S11A	11AC
National	JA	14A	6A	A	PA	SA	MA	CA
	–	ZA	–	–	BA	WA	–	CKA
	–	24A	–	–	HA	–	–	–
	–	34A	–	–	–	–	–	–
	–	ZMA	–	–	LA	–	–	–
	–	–	–	–	BKA	–	–	–
Ney Abrasives	–	–	–	RW	A	WA	HA	CA
Norton	–	66A	–	A	57	32	16	AC
	–	68A	76A	–	–	38	19	–
	–	ZF	–	–	–	–	23	–
	–	ZS	–	–	–	–	53	–
	–	NZ	–	–	–	–	–	–
Osborn	3A	–	–	7A	2A	1A	–	AC
Pacific	–	19A	–	–	–	–	–	69A
	–	20A	–	A	35A	50A	40A	70A
	–	21A	–	–	–	–	–	–
	–	22A	–	–	–	47A	42A	71A
	–	–	–	–	–	49A	45A	72A
	–	–	–	–	–	–	–	73A
Red Hill	TA	ZA	–	A	FA	WA	HA	AC
	NA	XA	–	–	–	–	–	–
SGL Abrasives	3A	15A	–	A	14A	10A	HA	RA
	–	18A	–	–	4A	–	KA	EA
	–	20A	–	–	–	–	–	–
Universal	--	4A	–	A	FA	WA	WAA	CA
	–	4B	–	–	–	SA	WRA	FCA
	–	4D	–	–	–	RA (Ruby)	EAA	–
	–	–	–	–	–	EA (Em-Rald)	RFA	–
Waltham	A	28A	46A	A	–	BA	DA	–
	–	29A	47A	–	–	–	–	–
	–	48A	–	–	–	–	–	–
	21A	51A	–	–	2168A	25A	–	–
	–	54A	–	–	68A	WA	14A	CA
	–	30A	–	–	–	11A	24A	16A
	–	49A	–	–	–	12A	–	–
	–	53A	–	–	–	3A (Pink)	–	–
Westfield	TA	–	–	A	FA	75A	72A	CA
	–	–	–	–	77A	–	73A	76A
	–	–	–	–	–	–	74A	–

TABLE 20.1–3 Comparative Silicon Carbide Wheel Marking Symbols
(Includes both manufacturers' prefixes and abrasive symbols)

MANUFACTURER	HEAVY DUTY	REGULAR	SEMI-FRIABLE	FRIABLE	SILICON CARBIDE MIXTURE
Acme	—	C	—	GC	—
Bancroft	C	C	—	GC	—
Bay State	7C	C	—	1C	—
Bendix	SC	C	—	GC	MC
	—	C	—	GC	HC
Blanchard	—	C	—	9C	—
Brightboy	—	S1C	—	—	—
	—	S	—	—	—
Buckeye	HC	C	—	GC	CA
Carborundum	TC	C	SC	GC	RC
	WC	—	BC	—	—
Chicago	—	49C	—	49CG	47C
	—	—	—	48C	—
Cincinnati	—	6C	—	5C	7C
Colonial	C	C	—	GC	—
de Sanno	HC	C	—	GC	GCC
Eomar	HC	C	FC	GC	MC
Ferro (FMR Electro)	TC	C	—	GC	RC
Fisher	—	C	—	GC	—
Gardner	—	C	—	GC	AC
	—	—	—	SC	—
Hanson	HC	—	—	GC	4C
ITT Abrasive	C	C	—	GC	SC
Jowitt & Rodgers	—	X	—	GC	—
MWA	C	3C	—	7C	3C
National	—	C	—	GC	RC
Ney Abrasives	—	C	—	GC	—
Norton	—	37C	—	39C	74C
Osborn	3C	—	—	1C	—
Pacific	—	75C	—	80C	77C
Red Hill	—	C	—	GC	—
SGL Abrasives	—	C	—	7C	—
Universal	—	C	BC	GC	—
Waltham	21C	C	—	GC	LC
	—	C	—	—	MC
Westfield	—	C	—	GC	—
Bullard	C	FC	GC	6C	—

SOURCE: Grinding Wheel Institute.

20.1 Grinding Wheels

CUBIC BORON NITRIDE (CBN) GRINDING WHEELS

Applications

CBN grinding wheels are recommended for alloys that are difficult to grind with conventional abrasives; that is, steels and cast irons with hardnesses above 50 R_C and nickel and cobalt high temperature alloys with hardnesses above 35 R_C.

Wheel Identification

Table 20.1-4 shows the standard marking system for diamond and cubic boron nitride abrasives (per ANSI B74.13-1977). Table 20.1-5 lists the codes that are used by the various wheel manufacturers for these abrasives.

Bond Types

CBN grinding wheels are available with resinoid, vitrified and metal bonds. Resinoid-bond wheels produce a good finish at high metal removal rates and provide fairly good wheel life. Vitrified-bond wheels are better for holding form and provide longer wheel life. Metal-bond wheels are free cutting and give high metal removal rates.

Metal-Lond, electroplated wheels contain a single layer of CBN grains and cannot be trued or dressed. Therefore, it is imperative that the spindle be running true and that all mounting surfaces be clean and free of burrs. When these wheels are mounted, the runout should not exceed 0.0005 inch [0.013 mm] TIR in either the radial or the lateral directions.

Grit Size

Because of the sharpness of CBN, it is necessary to use finer grain sizes than are used with conventional abrasives to obtain the same surface roughness level. Extremely fine finishes are difficult to obtain with CBN abrasives because there is little or no burnishing of the surface since CBN abrasives wear so little.

Grinding Fluids

Hardened steels and cast irons can be ground dry with CBN wheels; however, using a grinding fluid will improve both the surface roughness and the wheel life. A light-duty soluble oil will suffice for these materials.

When grinding the superalloys, a heavy-duty, active grinding fluid, that is, sulfo-chlorinated oil or sulfo-chlorinted soluble oil, is a must These heavy-duty grinding fluids will also improve grinding ratios when grinding hardened steels with CBN wheels

Truing and Dressing

It is of utmost importance that a CBN wheel be properly conditioned before attempting to grind with it. Both resinoid-bond and vitrified-bond wheels can be trued using a rotary diamond dresser, a brake-controlled truing device or a metal-bonded, 100 to 180 mesh size diamond truing tool. A single-point or cluster diamond should not be used. The wheel should be flooded with a copious supply of coolant while truing.

After truing, resinoid-bond CBN wheels must be dressed to open up the glazed surface left by the truing process. A conditioning stick containing approximately 200-mesh aluminum oxide or silicon carbide abrasives in a soft vitrified bond can be used. It is best to jog the wheel and press the conditioning stick into the wheel while it is slowing down. This removes the bond, exposing the sharp cutting edges. When the conditioning stick starts to wear rapidly, the wheel is properly dressed. Vitrified-bond CBN wheels usually do not need to be dressed or conditioned. They can be used immediately after truing.

Machine Requirements

To realize maximum benefits from using CBN wheels, the machine must have sufficient rigidity, horsepower and spindle speed. Machine vibrations that can be tolerated with conventional abrasives because of their more rapid wheel breakdown will cause CBN wheels to chatter.

Surface Integrity

Because CBN wheels remain sharp longer, they produce less heat and deformation in the workpiece, thus less residual stress. This permits the use of conventional speeds and feeds on critical parts that would otherwise require "low stress" grinding procedures if conventional abrasives were used.

TABLE 20.1–4 Markings for Identifying Diamond and Cubic Boron Nitride Grinding Wheels and Other Bonded Abrasives
(*Standard marking system chart per ANSI B74.13-1977*)

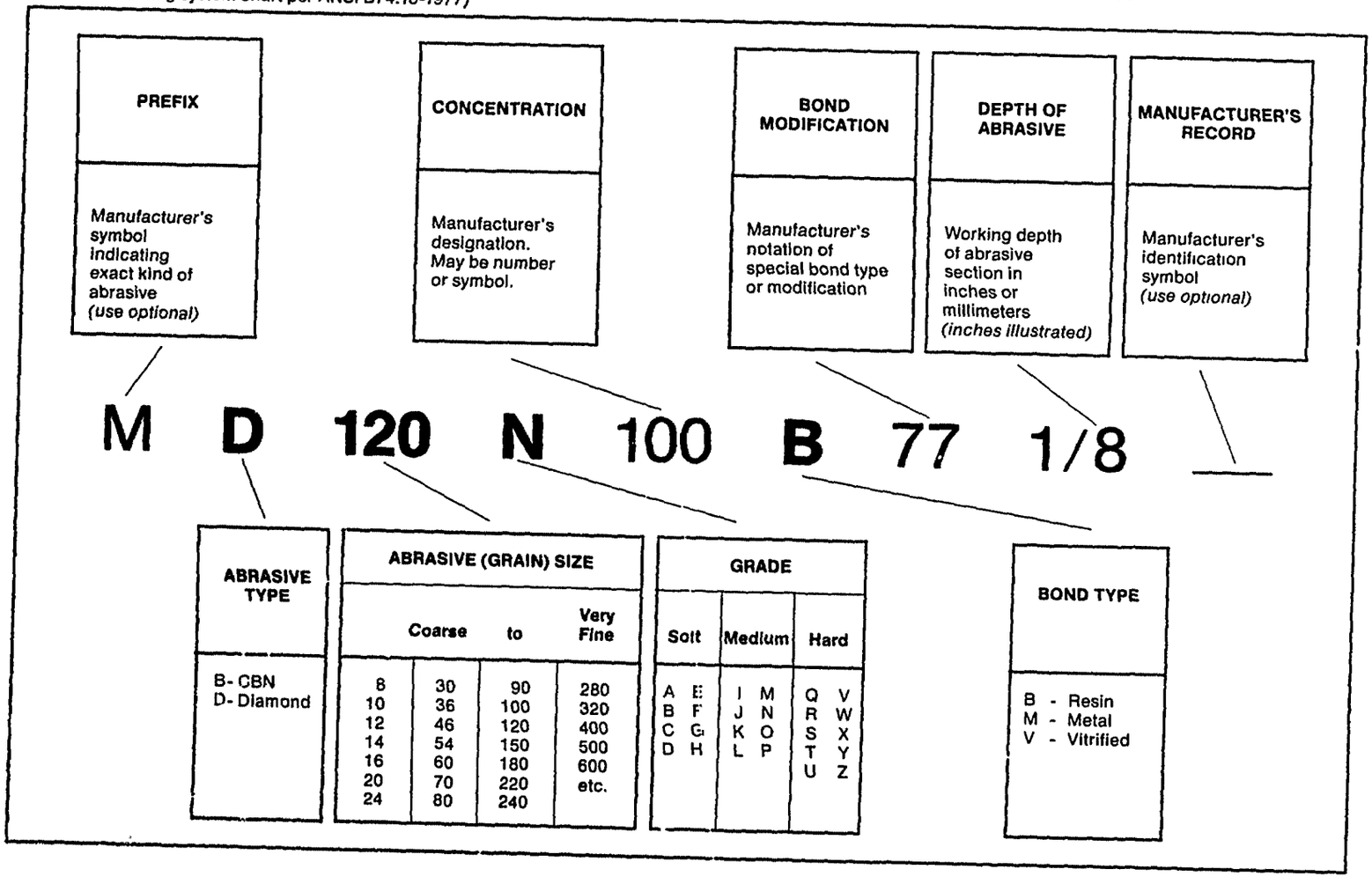


TABLE 20.1–5 Comparative Diamond and Cubic Boron Nitride Wheel Marking Symbols

MANUFACTURER	CUBIC BORON NITRIDE	DIAMOND
Bay State	1B (Borazon)	D, 1D, 3D, 4D, 6D, 9D
Bendix	B (Cubic boron nitride)	D (Manufactured)
Carborundum	CB (Nickel-coated resin-bond cubic boron nitride) B (uncoated cubic boron nitride)	D MD (Manufactured) CMD (Coated manufactured) SND (Selected natural)
Cincinnati	1BN (Metal-coated cubic boron nitride) 2BN (Cubic boron nitride)	MD (Manufactured) CMD (Coated manufactured) AMD (Coated manufactured) EMD (Coated manufactured) DMD (Coated manufactured)
Norton	CB (Cubic boron nitride)	D SD (Manmade) ASD (Coated manufactured) ASDC (Coated manufactured) AZD (Coated manufactured)
Universal	BZ (Borazon)	D (Natural) CD (Coated natural) MD (Manufactured) WD (Metal coated manufactured) DD (Metal coated manufactured) SD (Metal coated manufactured)
Waltham	BN (Borazon)	MD (Manufactured) D (Natural) ND (Manufactured nickel coated) CD (Manufactured copper coated)

SOURCE: Grinding Wheel Institute.

DIAMOND GRINDING

Diamond grinding technology has developed considerably during the past 30 years with respect to both grinding wheels with natural grit and, more recently, grinding wheels with synthetic grit. Today, diamond wheels are available in a large variety of mesh sizes, diamond concentrations, and bond types. Table 20.1-4 lists the standard markings used for diamond wheels. The designations for abrasive types used by various wheel manufacturers are listed in table 20.1-5.

Grain types have been developed for specific grinding operations and materials. More recent developments have opened up new applications for diamond wheels, especially in the field of steel and carbide grinding utilizing metal-clad, diamond-grain wheels.

Diamond wheels are available in several bonds: metal, vitrified and resinoid. Each bond type provides different results, depending on the type of grinding operation and the material being ground.

Metal-bond wheels are extremely strong, long-life wheels having diamonds securely held in a metal matrix. Chief uses are cutoff operations with thin wheels, offhand grinding, chip-breaker grinding and electrolytically assisted grinding. Metal-bond wheels should always be used with a coolant.

Vitrified-bond wheels are diamonds bonded together with ceramic materials. This bond type provides long wheel life at good grinding rates. The principal applications for vitrified-bond diamond wheels are surface grinding, cylindrical grinding, offhand grinding and internal grinding.

Resinoid-bond wheels are the most popular type because they provide excellent grinding speed and relatively long life. A resinoid diamond wheel is ideally suited for grinding carbide cutting tools where maximum protection from heating and cracking are a consideration. This type of bond is best for machine grinding operations, such as cutter grinding, surface and cylindrical grinding. Resinoid bond has excellent form holding qualities, is easily dressed, and is most suitable for diamond wheels with formed faces.

Wet Grinding

Wherever possible, diamond wheels should be used wet. This promotes longer wheel life, decreases workpiece surface roughness and reduces wheel dressing frequency. For machines not equipped with flood coolant systems or where the operator must observe the work at all times, the mist or wick method can be used. The primary reason for recommending wet grinding with diamond wheels is that the diamond itself has a relatively low thermal threshold and will "burn" at relatively low (1,100° to 1,300°F [600° to 700°C]) temperatures. The heat at the crystal-work interface can easily reach the low temperature range in dry grinding.

Wet grinding with diamond wheels eliminates some of the common problems associated with dry grinding. Since workpiece temperatures are kept at a low level, the potential for surface cracks or possible catastrophic cracking of the workpiece is greatly reduced. Dust problems also are eliminated. The flushing action of a copious supply of coolant helps to keep the diamond wheel cutting free, thus preventing loading of the wheel.

Dry Grinding

If dry grinding is absolutely necessary, wheel speed must be kept below 4,500 feet per minute [23 m/s], with 3,500 to 4,000 feet per minute [18 to 20 m/s] preferable. With care and practice, an experienced operator can become proficient at dry grinding of hard materials such as carbide and ceramics. One problem associated with dry grinding is dust; therefore, adequate dust-collecting systems need to be employed. Wheel wear will be greater than with wet grinding because softer wheels must be used to help keep the grinding temperatures as low as possible. Although resinoid-bond wheels are recommended for dry diamond grinding of hard, brittle materials such as carbide, glass and ceramics, high grinding temperatures can burn or crack the grinding wheel. Metal- and vitrified-bond diamond wheels, on the other hand, if run dry on hard, brittle materials may cause cracking of the workpiece material.

Machines for Grinding with Diamonds

Diamond grinding requires a higher level of machine tool integrity than might be required for grinding with a silicon carbide or an aluminum oxide wheel. Spindles must run true, bearings should be in good condition and good maintenance procedures should be followed.

Wheel Mounting

When mounting a diamond wheel, extra care should be taken to be sure that back plates, flanges and spindles are clean, free of burrs and running true. Straight wheels should be tightened gently between the flanges and then lightly tapped into position so that they run within 0.0005 inch [0.013 mm] TIR. The flanges should then be completely tightened.

If the grinding machine has a tapered spindle nose, it is common practice to mount each diamond wheel on a separate collet or adaptor. If left as a unit, the mounted wheel and adaptor can then be removed and replaced as needed, and the time and abrasive lost in truing can be avoided.

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GRINDING RECOMMENDATIONS

The grinding conditions listed in section 8 of this handbook are provided as starting recommendations. These starting conditions may have to be adjusted to reflect (1) workpiece characteristics, (2) requirements for the ground surface, (3) economic objectives and (4) operational conditions. Obviously, these grinding recommendations represent only an approximation of the optimum conditions achievable by testing and experimenting.

These recommendations should handle most grinding situations. In a job shop, it is often necessary to avoid wheel changes; a few general-purpose wheels usually are used to grind almost every type of material, even if at less than optimum efficiency. Where large production quantities are involved, testing and modifications may be necessary to obtain optimum results.

Despite the use of standard grinding wheel markings (table 20.1-1), wheels with identical markings made by various manufacturers may vary in actual performance. Individual wheel makers have their own modifications of both abrasive and bond which cannot be included in the data tables. Likewise, the structure number is omitted from the wheel identification because its significance differs among various makes of wheels. The structure provides chip clearance and is also a result of grain size and proportion of bond. The best or standard structure is usually derived for most grain size and grade combinations as a result of experience and testing. The manufacturers of grinding wheels publish their tables of wheel recommendations which include grain modifications as well as structure numbers.

Recommendations in section 8 are predicated on average shop conditions. Deviations from such basic conditions will generally affect the manner in which grinding wheels perform. Some of the variables discussed later have opposing effects and may balance each other when present concurrently. Other variables can have similar effects which can be expected to work additively. An understanding of the directions in which process variables interact with grinding wheel performance permits modification of the controllable variables to improve overall operating conditions or economics.

MODIFYING WHEEL RECOMMENDATIONS

The following list of guidelines are provided for use in modifying the grinding wheel recommendations provided in section 8 to improve production or to meet the specific requirements of an application. No application, however, should be so finely tuned that normal variations would affect the output rate or the quality. The best approach is to accommodate any variations likely to occur. The best wheel for any application is the one that compromises the ability to cut rapidly with the ability to hold form, maintain surface roughness requirements and last longer.

Wheels recommended in section 8 are suitable for both rough and finish grinding in one setup. Where two setups are used, use a wheel one grade harder for roughing and a wheel one grade softer for finishing.

General Guidelines

- To remove a substantial amount of stock—wet grinding is recommended over dry grinding.
- To remove stock faster—use a coarser grain wheel with a more open structure and a less friable abrasive.
- To produce a smoother finish—use a finer grain wheel with a denser structure and a less friable abrasive. (See table 20.3-1.)
- To generate form—use a finer grain wheel with a more dense structure. (See table 20.3-3.)
- To grind large areas—use a softer grade and coarser grain wheel.
- To grind small areas—use a harder grade and a finer grain wheel.
- To grind soft metals—use a harder grade and a coarser grain wheels.
- To grind hard metals—use a softer grade and a finer grain wheel.
- To improve workpiece finish—dress the wheel to a fine finish.
- To minimize heat, warpage and surface damage in the workpiece—maintain wheel sharpness (see section 18.3, Surface Integrity).
- If the grinding wheel breaks down too fast—use a wheel with a less friable abrasive, a harder grade and a denser structure.
- If the grinding wheel glazes and burns—use a wheel with a more friable abrasive, a softer grade and a more open structure.

Guidelines for Surface Grinding

- To minimize heat and warpage in the workpiece—use fast table speeds, light downfeeds, and dress the wheel before final size.
- To improve workpiece finish—dress the wheel to a fine finish.
- When using wheels larger than 14-inch [356 mm] diameter—use one grade softer bond.

Guidelines for Surface Grinding, Vertical Spindle, Rotary Table

- To produce smoother workpiece finish and closer tolerances—use faster table speed, lighter downfeed and proper sparkout.
- To increase material removal rate—increase table speed and downfeed rate.

20.2 Grinding Guidelines

Guidelines for Cylindrical Grinding

- When using wheels larger than 14-inch [356 mm] diameter—use one grade softer bond.
- For heavier stock removal—use a faster traverse speed and a slower work speed and/or increase the depth of cut.
- To improve workpiece finish—use a slower traverse speed and a faster work speed and/or decrease the depth of cut.
- When using wider wheels—use a softer grade wheel (infeed grinding).
- When using narrower wheels—use a harder grade wheel (infeed grinding).

Guidelines for Centerless Grinding

- When using wheels smaller than 20-inch [500 mm] diameter—use a one grade harder wheel.
- To improve workpiece finish—use a smaller angle of draw and a faster regulating wheel speed.
- For heavier stock removal—use a larger angle of draw and a slower regulating wheel speed and grind closer to center.
- To produce roundness—grind as high above center as possible.
- To grind long bars—grind below center on a flat blade.

Guidelines for Internal Grinding

- For long bores—use softer grade wheels and wider wheels, if possible.
- For low powered machines—use softer grade wheels.
- For light spindle machines—use softer grade wheels.

MODIFYING OPERATING CONDITIONS TO CHANGE WHEEL GRADE ACTION

Most grinding problems (other than those related to machine condition) arise from the action of the wheel grade (or hardness) which is a direct function of the wheel sharpness or wear rate. Indicators of too little wear (that is, the wheel is acting hard) are: the wheel glazing, loading or not cutting freely; workpieces with burning, heat checking (grinding cracks) or out of roundness; finishes getting progressively better (due to glazing); and finely spaced chatter marks or squealing. Indicators of too much wear (that is, the wheel is acting soft) are: the wheel breaking down too fast; workpieces with finishes getting progressively worse; widely spaced chatter marks; and scratches, fishtails, taper or lack of accuracy.

The action of the wheel grade can be altered by adjusting the other grinding conditions to achieve proper grinding action when it is not desirable or possible to change the wheel. Table 20.2-1 contains guidelines for modifying wheel action.

TABLE 20.2-1 Guidelines for Modifying Wheel Action

OPERATION	To Make Wheel Act HARDER	To Make Wheel Act SOFTER
Internal grinding	Decrease work rpm Decrease wheel reciprocation Increase wheel rpm Dress wheel at slower rate	Increase work rpm Increase wheel reciprocation Decrease wheel rpm Dress wheel at faster rate
Surface grinding	Decrease table speed Decrease crossfeed Increase wheel rpm Dress wheel at slower rate	Increase table speed Increase crossfeed Decrease wheel rpm Dress wheel at faster rate
Cylindrical grinding (traverse)	Decrease traverse speed Increase wheel rpm Dress wheel at slower rate	Increase traverse speed Decrease wheel rpm Dress wheel at faster rate
Centerless grinding	Decrease feed wheel rpm Dress grinding wheel at slower rate	Increase feed wheel rpm Dress grinding wheel at faster rate

PRECAUTIONS

Safety

Follow all requirements for safe wheel use. Do not exceed the maximum speed marked on the wheel or shown in ANSI B7.1-1978, *Safety Requirements for the Use, Care, and Protection of Abrasive Wheels.* See table 20.2-2.

Cutting Fluids

Use the proper cutting fluid, use the proper flow rates, and direct the fluid so that is reaches the cutting zone. See section 16, Cutting Fluids.

Surface Integrity

To avoid damage to the ground surface in the form of grinding burn, heat checks (grinding cracks), warpage, residual stress or other surface alterations, see section 10.4, Low Stress Grinding, for proper grinding procedures. Also see section 18.3, Surface Integrity.

20.2 Grinding Guidelines

TABLE 20.2–2 Standard Maximum Wheel Speeds

CLASSIFICATION NUMBER	TYPES OF WHEELS	MAXIMUM WHEEL SPEED, fpm					
		INORGANIC BONDS			ORGANIC BONDS		
		Low Strength	Medium Strength	High Strength	Low Strength	Medium Strength	High Strength
1	Type 1—Straight Wheels—except classifications 6, 7, 9, 10, 11, 12, 13 and 14 below. Type 4*—Taper Side Wheels Types 5, 7, 20, 21, 22, 23, 24, 25, 26 Recessed, Dovetailed and/or relieved wheels. (Except Classification 7 and 14 below.) Type 12—Dish Wheels Type 13—Saucer Wheels Types 16, 17, 18, 19—Cones and Plugs	5,500	6,000	6,500	6,500	8,000	9,500
2	Type 2—Cylinder Wheels including plate mounted, inserted nut and projecting stud—Segments	5,000	5,500	6,000	5,000	6,000	7,000
3	Cup Shape Tool Grinding Wheels (For Fixed Base Machines) Type 6—Straight Side Cups Type 11—Flaring Cups	4,500	5,000	6,000	6,000	7,500	8,500
4	Cup Shape Snagging Wheels (For Portable Machines) Type 6—Straight Side Cups Type 11—Flaring Cups	4,500	5,500	6,500	6,000	8,000	9,500
5	Abrasive Discs: Plate Mounted Inserted Nut and Projecting Stud: Solid or Segmental	5,500	6,000	6,500	5,500	7,000	8,500
6†	Reinforced Wheels Type 1 Max. Dia. 4" Max. Thickness 1/4"	NA‡	NA	NA	9,500	12,500	16,000
	Max. Dia. 10" Max. Thickness 1/2"	NA	NA	NA	9,500	12,500	14,200
	All Other Diameters and Thicknesses	NA	NA	NA	9,500	12,500	12,500
	Reinforced Wheels—Types 27 and 28 Max. Dia. 9" Max. Thickness 3/8"	NA	NA	NA	9,500	12,500	14,200
	Max. Dia. 9"—Over 3/8" Thick	NA	NA	NA	NA	9,500	11,000
7	Type 1 Wheels for Bench and Pedestal Grinders Types 1 and 5 for Surface Grinders only in sizes 7" dia. up to 2" thick and up to 2" hole	5,500	6,325	6,600	6,500	8,000	9,500
	8" dia. up to 2" thick and up to 2" hole	5,500	6,325	7,550	6,500	8,000	9,500
8	Diamond and Cubic Boron Nitride Wheels	NA	NA	6,500	NA	NA	9,500
	Exceptions: 1. Metal Bond	NA	NA	12,000	NA	NA	NA
	2. Steel Centered Cutting-off Wheels	NA	NA	16,000	NA	NA	16,000
9	Cutting-off Wheels Type 1 and 27A Larger than 16" dia., Including Reinforced Organic	NA	NA	NA	9,500	12,000	14,200
10	Cutting-off Wheels Type 1 and 27A 16" dia., and Smaller—Including Reinforced Organic	NA	NA	NA	9,500	12,000	16,000
11	Thread and Flute Grinding Wheels	8,000	10,000	12,000	8,000	10,000	12,000
12	Crankshaft and Camshaft Grinding Wheels	5,500	8,000	8,500	6,500	8,000	9,500
13	Type 1 Snagging Wheels 16" diameter and larger, Organic bond including reinforced: Used on swing frame grinders, designed for this speed	NA	NA	NA	NA	NA	12,500
	Used on semi-automatic snagging grinders, designed for this speed	NA	NA	NA	NA	NA	16,500
14	Internal Wheels—Type 1 and 5 Maximum dia. 6"	5,500	8,000	8,500	6,500	8,500	9,500
15	Mounted Wheels (See standard for limitations)	NA	NA	10,000	NA	NA	10,000

SOURCE: ANSI B7.1-1978, p. 65

NOTE: Abrasive wheels are produced in a wide range of specifications to perform satisfactorily in a wide range of grinding applications. As a general rule, hard material requires a soft grade wheel and soft material is best ground by a hard grade wheel. Different wheel grades have different strengths; harder grade wheels are generally stronger than softer grade wheels, although other ingredients such as grit size, structure and bond type play a part in the overall strength of an abrasive wheel specification. Therefore, the maximum allowable operating speeds vary depending on the strength of the wheel. It is for this reason that speeds shown are listed in columns labeled Low, Medium, and High Strength.

*Non-standard shape.

†Classification 6 excludes cutoff wheels.

‡NA = not applicable.

SURFACE ROUGHNESS

The grain size of a grinding wheel will determine the approximate surface roughness that can be obtained on the workpiece, as given in table 20.3-1. The structure of the wheel and the dressing procedure will also affect the surface roughness to some degree. A finer-grain-size wheel will usually produce surfaces with lower roughness values at some sacrifice of stock removal capability.

Obtaining surface roughness values of less than 10 to 15 microinches R_a (0.25 to 0.38 μm) requires special attention to work speeds and crossfeed or traverse rates. Very smooth surfaces require abrasive grain sizes of 220 and finer.

TOLERANCES

The tolerances achievable with various grinding operations are given in table 20.3-2. The production tolerances can be held without difficulty; however, larger tolerances where acceptable will be more economical. The precision tolerances can be held with care but will be more costly.

Form Requirements

Grinding of forms and fillets usually requires the use of 80 grain size and finer wheels, as indicated in table 20.3-3.

Thread Grinding Requirements

In conventional grinding, the standard practice is to use the coarsest practical grain size for fastest stock removal. In thread grinding, however, the coarsest practical grain size is limited by the maximum allowable radius at the bottom of the thread. This radius is usually given in terms of root width, which is the distance between the points of tangency of the arc and the sides of the teeth. The root width varies inversely with the number of threads per inch (or metric pitch): the greater the number of threads per inch, the smaller the maximum allowable root width.

To alter the wheel recommendations in section 8.14, table 20.3-4 may be used as a guide for selecting the coarsest allowable grain size for a thread grinding wheel. If a particular standard calls for a narrower root width, the grain size must be chosen for the maximum allowable root width. Another factor to be considered is the quality of the finish. Where a very low surface roughness value is required on threads of relatively coarse pitch, it is advisable to use a finer grain wheel than would be necessary to hold the proper root width.

TABLE 20.3-1 Grinding Wheel Grain Sizes for Producing Various Surface Roughnesses

GRAIN SIZE	SURFACE ROUGHNESS	
	μin	
46	32	
54	20 to 32	
60	15 to 20	
80	10 to 15	
120	8 to 10	

20.3 Surface Roughness and Tolerances

TABLE 20.3-2 Production and Precision Grinding Tolerances

GRINDING OPERATION	TOLERANCES (Plus or Minus)			
	inch		mm	
	Production	Precision	Production	Precision
CYLINDRICAL GRINDING				
Diameters	0 00025	0.00001	0.0064	0.00025
Shoulders				
Shoulder to Shoulder	0.00025	0.0005	0.0064	0.0127
Traverse Grinding to a Shoulder	0.002	0.001	0.050	0.025
Corners and Radii				
External Corners	Sharp	Sharp		
Internal Corner Radii	0.005	0.0025	0.13	0.063
Spherical Sections (oscillating grinders)				
Diameters	0.00015		0.0038	
Location of Centers	0.001		0.025	
CENTERLESS GRINDING				
Diameters and Parallelism	0.0001	0.000025	0.0025	0.00064
Roundness	0 000012		0.0003	
Concentricity of Stepped Diameters	0.00025	0.0001	0.0064	0.0025
THREAD GRINDING				
Lead Error (inch per inch)	0.00025	0.00001	0.0064	0.00025
Pitch Diameter	0.0005	0.0002	0.0127	0.0050
Roundness	0.00025		0.0064	
Concentricity (thread form with OD)	0.0005		0.0127	
Grooves (width)	0.001		0.025	
SURFACE GRINDING				
Reciprocating Table Grinder				
Flatness	0.0002	0.00015	0.0050	0.0038
Thickness	0.0003	0.00015	0.0076	0.0038
Rotary Table Grinder				
Flatness	0 0002	0.0001	0.0050	0.0025
Parallelism	0.0002	0.00005	0.0050	0.0013
Thickness	0.001	0.0002	0.025	0.0050
INTERNAL GRINDING				
Holes (using automatic sizing devices)	0.00025	0.00005	0.0064	0.0013
Face Runout (squareness of shoulder to bore)	0.00025	0.00005	0.0064	0.0013

SOURCE. Adapted from H E. Trucks, *Designing for economical production,* Dearborn, MI. Society of Manufacturing Engineers, 1974, p. 34.

TABLE 20.3-3 Grinding Wheel Grain Sizes for the Radius of Forms or Fillets

GRAIN SIZE	MINIMUM RADIUS	
	inch	mm
80	0.010	0.254
120	0.007	0.178
180	0.005	0.127
220	0.004	0.102
280	0.003	0.076
320	0.002	0.051
500	0.001	0.025

TABLE 20.3–4 Coarsest Allowable Grain Sizes for Thread Grinding Wheels

AMERICAN STANDARD UNIFIED THREADS		COARSEST ALLOWABLE GRAIN SIZE		IFI-500 TRIAL METRIC THREADS*	
Threads Per Inch	Root Width in	Vitrified Wheels	Resinoid Wheels	Pitch	Root Width mm
80	0.0016	240	220	0.35	0.044
72	0.0017	240	220	—	—
64	0.0019	220	180	—	—
—	(0.0020)	220	180	0.40	0.050
56	0.0022	220	180	0.45	0.056
—	(0.0024)	220	180	0.50	0.062
48	0.0026	220	180	—	—
44	0.0028	220	180	—	—
—	(0.0029)	220	180	0.60	0.075
40	0.0031	220	180	—	—
36	0.0034	180	180	—	—
—	(0.0035)	180	180	0.70	0.088
32	0.0039	180	150	0.80	0.100
28	0.0045	150	120	—	—
—	(0.0049)	150	120	1.00	0.125
24	0.0052	150	120	—	—
—	(0.0061)	120	120	1.25	0.156
20	0.0062	120	120	—	—
18	0.0069	120	100	—	—
—	0.0074	120	100	1.50	0.188
16	0.0078	120	100	—	—
—	0 0086	120	100	1.75	0.219
14	0.0089	100	100	—	—
13	0.0096	100	90	—	—
—	0.0100	100	90	2.0	0.250
12	0.0104	90	90	—	—
11	0.0113	90	90	—	—
—	(0.0123)	90	90	2.5	0.312
10	0.0125	90	90	—	—
9	0.0139	90	80	—	—
—	(0.0148)	90	80	3.0	0.375
8	0.0156	80	80	—	—
—	(0.0172)	80	80	3.5	0.438
7	0.0178	80	80	—	—
—	(0.0197)	80	80	4.0	0.500
6	0.0208	80	80	—	—
—	(0.0221)	80	80	4.5	0.562
—	(0.0246)	80	70	5.0	0.625
5	0.0250	80	70	—	—
—	(0.0271)	80	70	5.5	0.688
4.5	0.0278	80	70	—	—
—	(0.0295)	80	70	6	0.750
4	0.0312	70	70	—	—

SOURCE: Adapted from Thread Grinding, 18th Edition, 1963, published by Norton Company.

NOTES: Pitch = 1 ÷ number of threads per inch.
Root width = 0.125 × Pitch.

*Also applies to British Standard ISO Metric Threads.

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Grinding Formulas and Charts 20.4

Shop equations and data for determining pertinent information on various types of grinding operations are given in tables 20.4-1 through 20.4-4 and figures 20.4-1 through 20.4-7 as follows:

Table 20.4-1 Definitions of symbols used in grinding formulas and sketches, English units.

Table 20.4-2 Definitions of symbols used in grinding formulas, Metric units.

Figure 20.4-1 Sketches of various grinding operations

Table 20.4-3 Grinding formulas, English units.

Table 20.4-4 Grinding formulas, Metric units.

Figure 20.4-2 Unit power for surface traverse grinding: horizontal spindle—reciprocating table.

Figure 20.4-3 Unit power for centertype cylindrical plunge grinding.

Figure 20.4-4 Alignment chart for determining metal removal rate and horsepower required at motor: traverse grinding (reciprocating table) for horizontal and vertical spindle surface grinding.

Figure 20.4-5 Alignment chart for determining metal removal rate and horsepower required at motor: plunge grinding (reciprocating table) for horizontal and vertical spindle surface grinding.

Figure 20.4-6 Alignment chart for determining metal removal rate and horsepower required at motor: traverse grinding for centertype cylindrical, centerless and internal grinding.

Figure 20.4-7 Alignment chart for determining metal removal rate and horsepower required at motor: plunge grinding for centertype cylindrical, centerless and internal grinding.

20.4 Grinding Formulas and Charts

TABLE 20.4–1 Definitions of Symbols Used in Grinding Formulas and Sketches, English Units

- a = Depth of grind, inches per pass
- a_t = Total depth of grind, inches
- b = Width of cut in plunge grinding, inches
- b_c = Crossfeed, inches per pass
- b_s = Original width of grinding wheel, inches
- b_w = Width of workpiece, inches
- d_o = OD of grinding wheel, inches (vertical spindle surface grinder)
- d_i = ID of grinding wheel, inches (vertical spindle surface grinder)
- d_r = Regulating wheel diameter, inches (for centerless grinding)
- d_{s1} = Initial grinding wheel diameter, inches
- d_{s2} = Final grinding wheel diameter, inches
- d_t = Average diameter of workpiece path on rotary table, inches (vertical spindle surface grinder)
- d_{w1} = Original work diameter, inches
- d_{w2} = Final work diameter, inches
- E = Efficiency of grinding wheel drive
- f_t = Table traverse feed rate or throughfeed of work in centerless grinding, inches per minute
- f_p = Plunge infeed rate, inches per minute
- G = Grinding ratio = $\frac{\text{Volume metal removed, in}^3}{\text{Volume wheel wear, in}^3}$
- L = Length of workpiece ground, inches
- hp_g = Horsepower required at motor, hp
- n_r = Regulating wheel rpm
- n_s = Grinding wheel rpm
- n_t = Rotary table rpm (vertical spindle surface grinder)
- n_w = Work rpm
- P_g = Unit horsepower, horsepower per cubic inch per minute
- s = Feed per revolution of work, inches
- t = Axial wear from face of grinding wheel (vertical spindle surface grinder)
- v_s = Peripheral speed of grinding wheel, feet per minute
- v_w = Peripheral speed of work, feet per minute
- w_m = Maximum contact width of grinding wheel on work (vertical spindle surface grinder)
- Z = Metal removal rate, cubic inches per minute
- α = Regulating wheel inclination angle, degrees (centerless grinder)

TABLE 20.4–2 Definitions of Symbols Used in Grinding Formulas and Sketches, Metric Units

- a = Depth of grind, millimeters per pass
- a_t = Total depth of grind, millimeters
- b = Width of cut in plunge grinding, millimeters
- b_c = Crossfeed, millimeters per pass
- b_s = Original width of grinding wheel, millimeters
- b_w = Width of workpiece, millimeters
- d_o = OD of grinding wheel, millimeters (vertical spindle surface grinder)
- d_i = ID of grinding wheel, millimeters (vertical spindle surface grinder)
- d_r = Regulating wheel diameter, millimeters (for centerless grinding)
- d_{s1} = Initial grinding wheel diameter, millimeters
- d_{s2} = Final grinding wheel diameter, millimeters
- d_t = Average diameter of workpiece path on rotary table, millimeters (vertical spindle surface grinder)
- d_{w1} = Original work diameter, millimeters
- d_{w2} = Final work diameter, millimeters
- E = Efficiency of grinding wheel drive
- f_t = Table traverse feed rate or throughfeed of work in centerless grinding, millimeters per minute
- f_p = Plunge infeed rate, millimeters per minute
- G = Grinding ratio = $\frac{\text{Volume metal removed, mm}^3}{\text{Volume wheel wear, mm}^3}$
- L = Length of workpiece ground, millimeters
- kW_g = Power required at motor, kilowatts
- n_r = Regulating wheel rpm
- n_s = Grinding wheel rpm
- n_t = Rotary table rpm (vertical spindle surface grinder)
- n_w = Work rpm
- P_g = Unit power, kilowatts per cubic centimeter per minute
- s = Feed per revolution of work, millimeters
- t = Axial wear from face of grinding wheel, millimeters (vertical spindle surface grinder)
- v_s = Peripheral speed of grinding wheel, meters per second
- v_w = Peripheral speed of work, meters per minute
- w_m = Maximum contact width of grinding wheel on work, millimeters (vertical spindle surface grinder)
- Z = Metal removal rate, cubic centimeters per minute
- α = Regulating wheel inclination angle, degrees (centerless grinder)

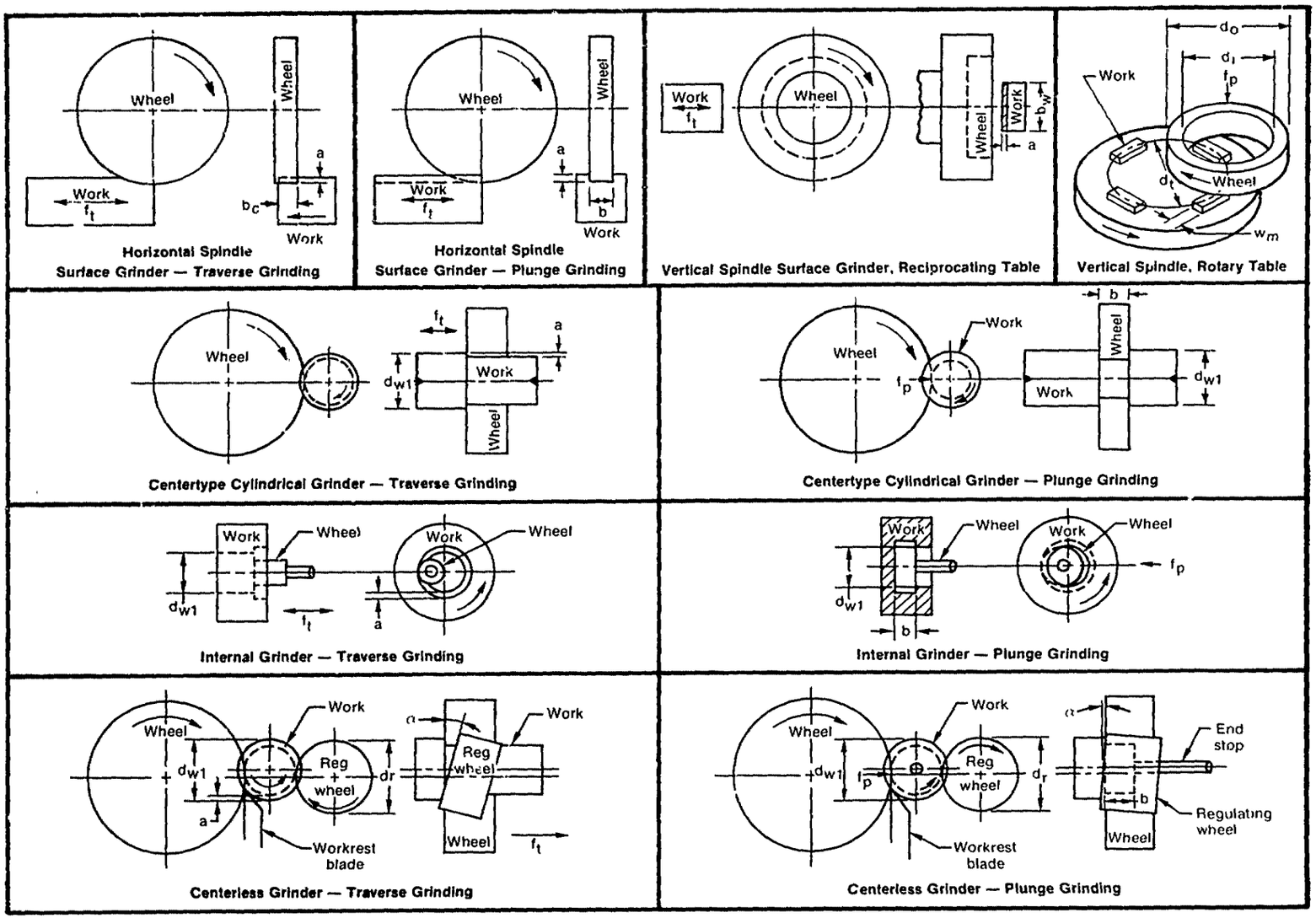


Figure 20.4–1 Sketches of various grinding operations. See tables 20.4–1 and 20.4–2 for definitions of symbols.

TABLE 20.4–3 Grinding Formulas, English Units

PARAMETER	SURFACE GRINDING			CENTERTYPE CYLINDRICAL GRINDING	CENTERLESS GRINDING	INTERNAL GRINDING
	HORIZONTAL SPINDLE	VERTICAL SPINDLE				
	Reciprocating Table	Reciprocating Table	Rotary Table			
Peripheral wheel speed, ft/min	$v_s = 0.262 \times d_s \times n_s$	$v_s = 0.262 \times d_s \times n_s$	$v_s = 0.262 \times d_s \times n_s$	$v_s = 0.262 \times d_s \times n_s$	$v_s = 0.262 \times d_s \times n_s$	$v_s = 0.262 \times d_s \times n_s$
Wheel rpm	$n_s = 3.82 \frac{v_s}{d_s}$	$n_s = 3.82 \frac{v_s}{d_s}$	$n_s = 3.82 \frac{v_s}{d_s}$	$n_s = 3.82 \frac{v_s}{d_s}$	$n_s = 3.82 \frac{v_s}{d_s}$	$n_s = 3.82 \frac{v_s}{d_s}$
Peripheral work speed, ft/min	v_w	v_w	$v_w = 0.262 \times d_w \times n_w$	$v_w = 0.262 \times d_{w1} \times n_w$	$v_w = 0.262 \times d_{w1} \times n_w$	$v_w = 0.262 \times d_{w1} \times n_w$
Work rpm	—	—	$n_w = \frac{3.82 \times v_w}{d_w}$	$n_w = 3.82 \times \frac{v_w}{d_{w1}}$	$n_w = 3.82 \times \frac{v_w}{d_{w1}}$	$n_w = 3.82 \times \frac{v_w}{d_{w1}}$
Horsepower at motor	$hp_g = \frac{P_g \times Z}{E}$	$hp_g = \frac{P_g \times Z}{E}$	$hp_g = \frac{P_g \times Z}{E}$	$hp_g = \frac{P_g \times Z}{E}$	$hp_g = \frac{P_g \times Z}{E}$	$hp_g = \frac{P_g \times Z}{E}$
TRAVERSE GRINDING						
Table traverse feed rate, in/min	f_t	f_t	—	$f_t = s \times n_w$	$f_t = \pi \times d_s \times n_s \times \sin \alpha$	$f_t = s \times n_w$
Metal removal rate, in³/min	$Z = a \times b_c \times f_t$	$Z = a \times b_w \times f_t$	—	$Z = \pi \times a \times f_t \times d_{w1}$	$Z = \pi \times a \times f_t \times d_{w1}$	$Z = \pi \times a \times f_t \times d_{w1}$
G ratio	$G = \frac{1.273 \times L \times b_w \times a_t}{b_s (d_{s1}^2 - d_{s2}^2)}$	$G = \frac{1.273 \times L \times b_w \times a_t}{t (d_o^2 - d_i^2)}$	—	$G = \frac{L (d_{w1}^2 - d_{w2}^2)}{b_s (d_{s1}^2 - d_{s2}^2)}$	$G = \frac{L (d_{w1}^2 - d_{w2}^2)}{b_s (d_{s1}^2 - d_{s2}^2)}$	$G = \frac{L (d_{w1}^2 - d_{w2}^2)}{b_s (d_{s1}^2 - d_{s2}^2)}$
PLUNGE GRINDING						
Feed rate, in/mm	f_t	f_t	$f_p = s \times n_t$	f_p	f_p	f_p
Metal removal rate, in³/min	$Z = a \times b \times f_t$	$Z = a \times b_w \times f_t$	$Z = \pi \times w_m \times f_p \times d_s$	$Z = \pi \times b \times f_p \times d_{w1}$	$Z = \pi \times b \times f_p \times d_{w1}$	$Z = \pi \times b \times f_p \times d_{w1}$
G ratio	$G = \frac{1.273 \times L \times b \times a_t}{b_s (d_{s1}^2 - d_{s2}^2)}$	$G = \frac{1.273 \times L \times b_w \times a_t}{t (d_o^2 - d_i^2)}$	$G = \frac{1.273 \times L \times b_w \times a_t}{t (d_o^2 - d_i^2)}$	$G = \frac{b (d_{w1}^2 - d_{w2}^2)}{b_s (d_{s1}^2 - d_{s2}^2)}$	$G = \frac{b (d_{w1}^2 - d_{w2}^2)}{b_s (d_{s1}^2 - d_{s2}^2)}$	$G = \frac{b (d_{w1}^2 - d_{w2}^2)}{b_s (d_{s1}^2 - d_{s2}^2)}$

See table 20.4-1 for definition of symbols.

TABLE 20.4 -4 Grinding Formulas, Metric Units

PARAMETER	SURFACE GRINDING			CENTERTYPE CYLINDRICAL GRINDING	CENTERLESS GRINDING	INTERNAL GRINDING
	HORIZONTAL SPINDLE	VERTICAL SPINDLE				
	Reciprocating Table	Reciprocating Table	Rotary Table			
Peripheral wheel speed, m/s	$v_s = 0.000052\ d_s \times n_s$	$v_s = 0.000052\ d_s \times n_s$	$v_s = 0.000052\ d_s \times n_s$	$v_s = 0.000052\ d_s \times n_s$	$v_s = 0.000052\ d_s \times n_s$	$v_s = 0.000052\ d_s \times n_s$
Wheel rpm	$n_s = 19231\ \frac{v_s}{d_s}$	$n_s = 19231\ \frac{v_s}{d_s}$	$n_s = 19231\ \frac{v_s}{d_s}$	$n_s = 19231\ \frac{v_s}{d_s}$	$n_s = 19231\ \frac{v_s}{d_s}$	$n_s = 19231\ \frac{v_s}{d_s}$
Peripheral work speed, m/min	v_w	v_w	$v_w = 0.0032\ d_w \times n_w$	$v_w = 0.0032\ d_w \times n_w$	$v_w = 0.0032\ d_w \times n_w$	$v_w = 0.0032\ d_w \times n_w$
Work rpm	—	—	$n_w = 318\ \frac{v_w}{d_w}$	$n_w = 318\ \frac{v_w}{d_w}$	$n_w = 318\ \frac{v_w}{d_w}$	$n_w = 318\ \frac{v_w}{d_w}$
Power at motor, kW	$kW_g = \frac{P_g \times Z}{E}$	$kW_g = \frac{P_g \times Z}{E}$	$kW_g = \frac{P_g \times Z}{E}$	$kW_g = \frac{P_g \times Z}{E}$	$kW_g = \frac{P_g \times Z}{E}$	$kW_g = \frac{P_g \times Z}{E}$
TRAVERSE GRINDING						
Table traverse feed rate, mm/min	f_t	f_t	—	$f_t = s \times n_w$	$f_t = \pi \times d_r \times n_r \times \sin\alpha$	$f_t = s \times n_w$
Metal removal rate, cm^3/min	$Z = \frac{a \times b_c \times f_t}{1000}$	$Z = \frac{a \times b_w \times f_t}{1000}$	—	$Z = \frac{\pi \times a \times f_t \times d_w}{1000}$	$Z = \frac{\pi \times a \times f_t \times d_w}{1000}$	$Z = \frac{\pi \times a \times f_t \times d_w}{1000}$
G ratio	$G = \frac{1.273 \times L \times b_w \times a_e}{t\,(d_s^2 - d_f^2)}$	$G = \frac{1.273 \times L \times b_w \times a_e}{t\,(d_s^2 - d_f^2)}$	—	$G = \frac{L\,(d_{s1}^2 - d_{w2}^2)}{b_s\,(d_{s1}^2 - d_{s2}^2)}$	$G = \frac{L\,(d_{s1}^2 - d_{w2}^2)}{b_s\,(d_{s1}^2 - d_{s2}^2)}$	$G = \frac{L\,(d_{s1}^2 - d_{w2}^2)}{b_s\,(d_{s1}^2 - d_{s2}^2)}$
PLUNGE GRINDING						
Feed rate, mm/min	f_r	f_t	$f_p = s \times n_r$	f_p	f_p	f_p
Metal removal rate, cm^3/min	$Z = \frac{a \times b \times f_t}{1000}$	$Z = \frac{a \times b_w \times f_t}{1000}$	$Z = \frac{\pi \times w_m \times f_p \times d_r}{1000}$	$Z = \frac{\pi \times b \times f_p \times d_w}{1000}$	$Z = \frac{\pi \times b \times f_p \times d_w}{1000}$	$Z = \frac{\pi \times b \times f_p \times d_w}{1000}$
G ratio	$G = \frac{1.273 \times L \times b \times a_e}{t\,(d_s^2 - d_f^2)}$	$G = \frac{1.273 \times L \times b_w \times a_e}{b_s\,(d_{s1}^2 - d_{s2}^2)}$	$G = \frac{1.273 \times L \times b_w \times a_e}{t\,(d_s^2 - d_f^2)}$	$G = \frac{b\,(d_{s1}^2 - d_{w2}^2)}{b_s\,(d_{s1}^2 - d_{s2}^2)}$	$G = \frac{b\,(d_{s1}^2 - d_{w2}^2)}{b_s\,(d_{s1}^2 - d_{s2}^2)}$	$G = \frac{b\,(d_{w1}^2 - d_{w2}^2)}{b_s\,(d_{s1}^2 - d_{s2}^2)}$

See table 20.4-2 for definition of symbols.

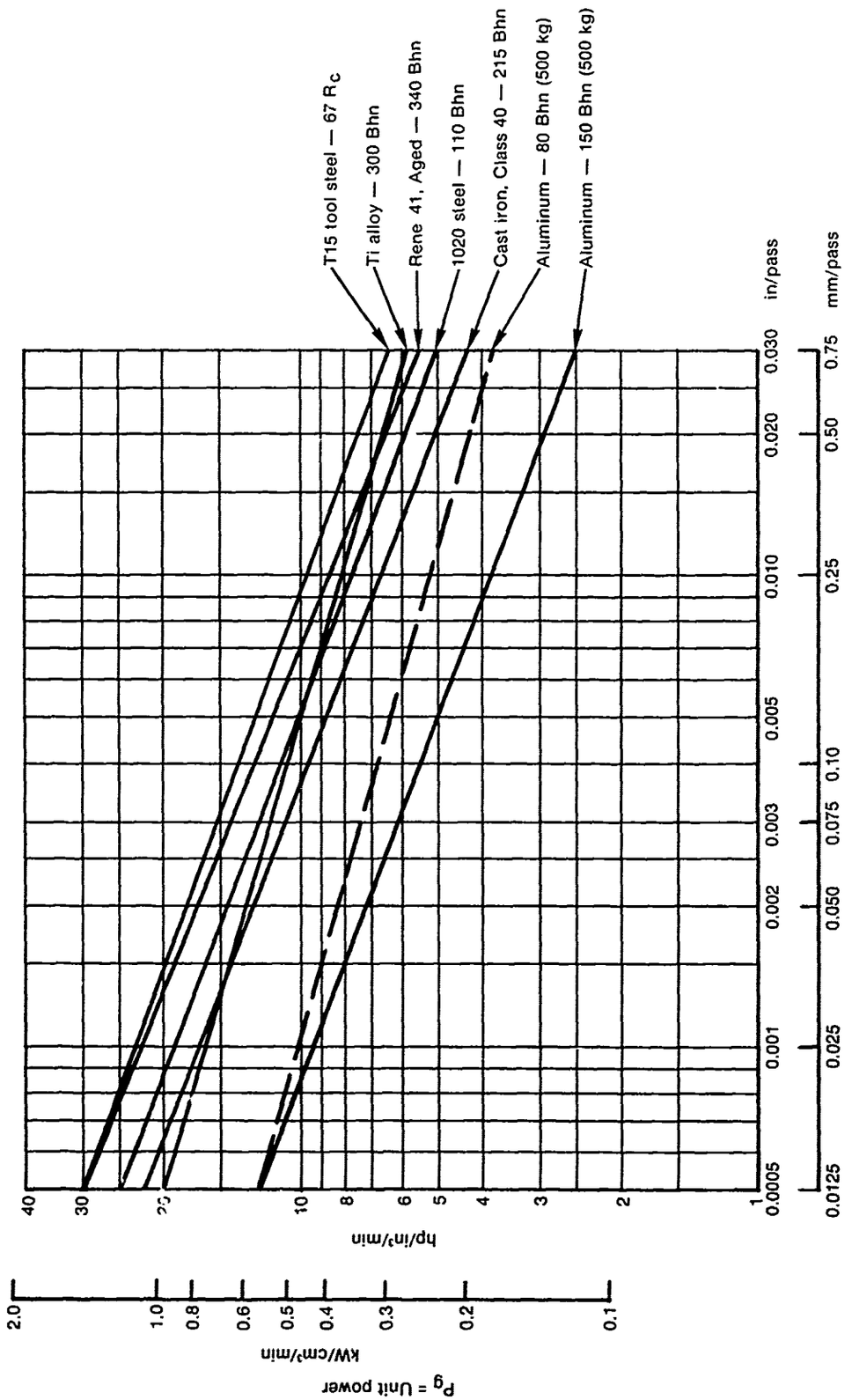


Figure 20.4–2 Unit power for surface traverse grinding: horizontal spindle—reciprocating table.

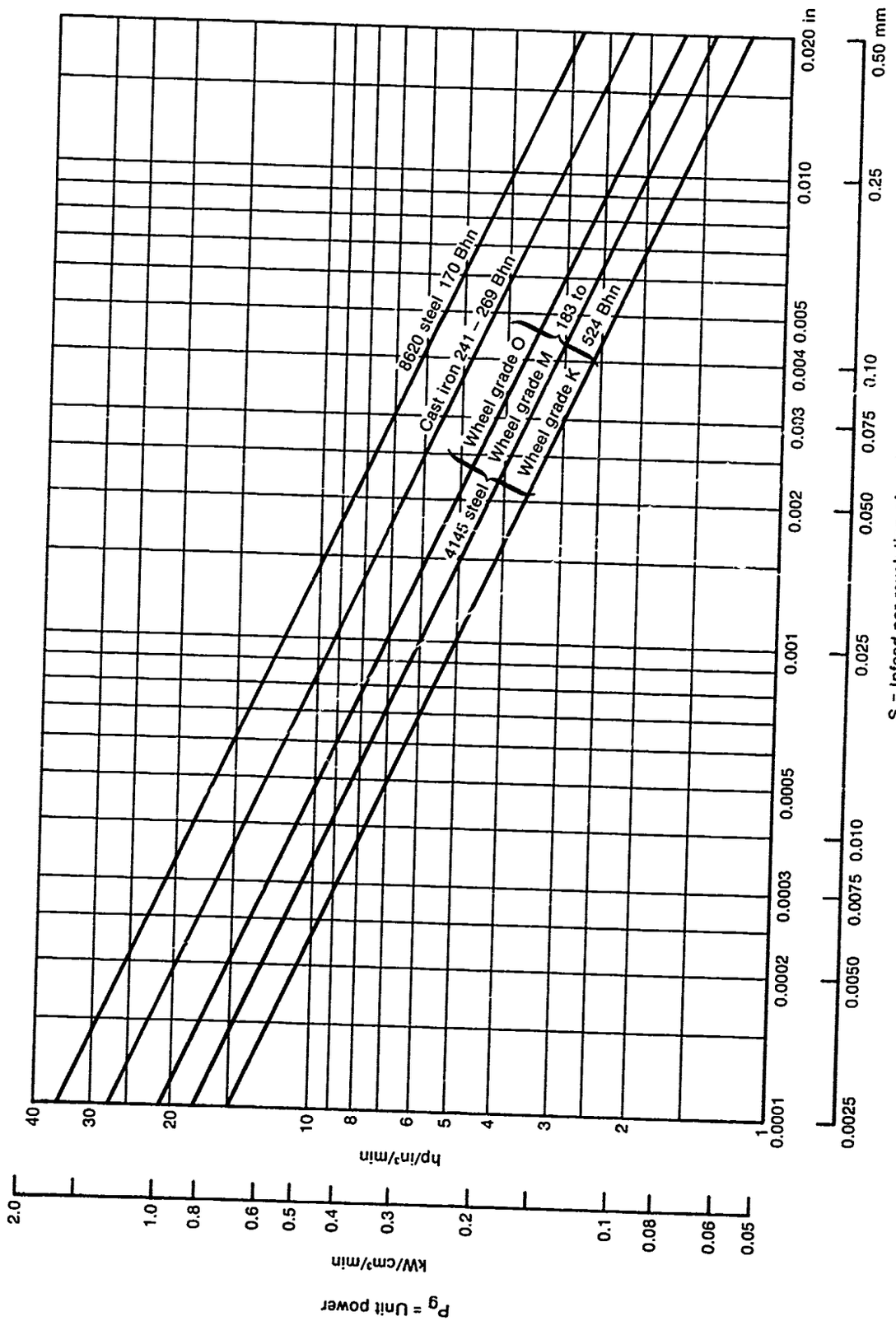


Figure 20.4–3 Unit power for centertype cylindrical plunge grinding.

20.4 Grinding Formulas and Charts

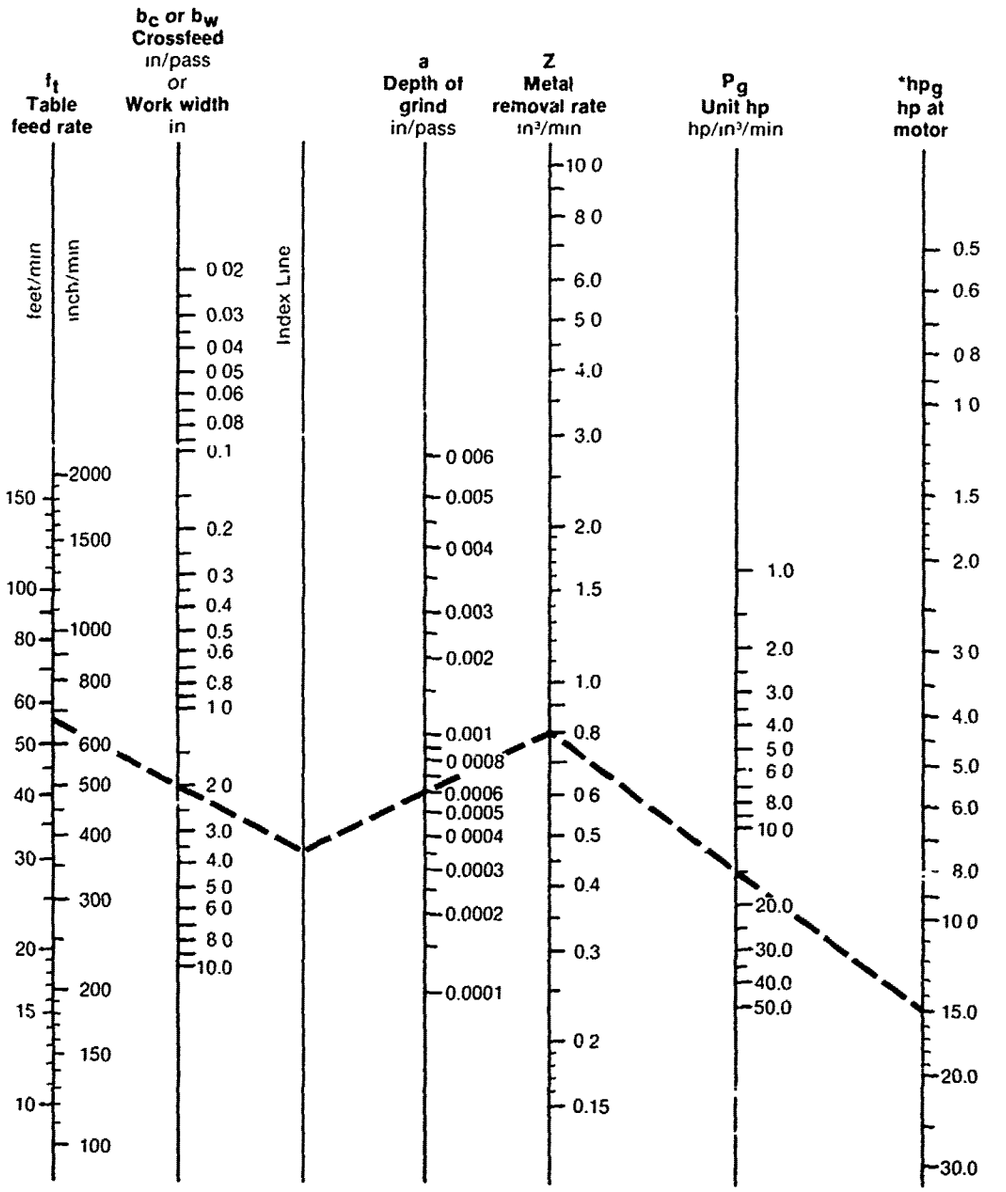
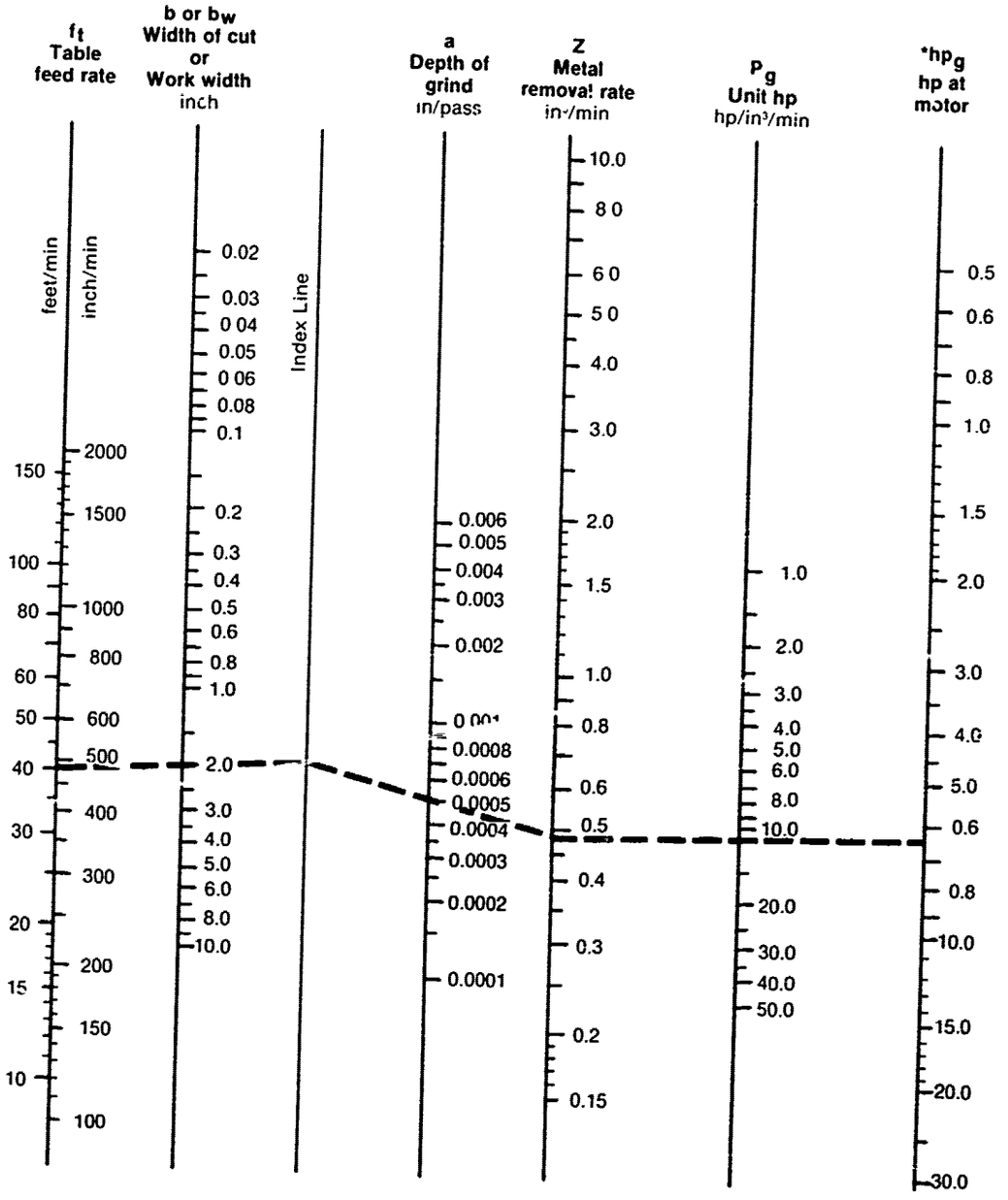


Figure 20.4–4 Alignment chart for determining metal removal rate and horsepower required at motor: traverse grinding (reciprocating table) for horizontal and vertical spindle surface grinding.



Example: Vertical spindle — Plunge grinding

1020 steel, 120 Bhn

Given: f_t = 40 ft/min b_w = 2 in a = 0.0005 in/pass

P_g = 10.5 hp/in³/min

Then: Z = 0.48 in³/min hp_g = 6.4 hp

Plunge grinding: $Z = f_t \times b \times a$ (Horiz. spindle)

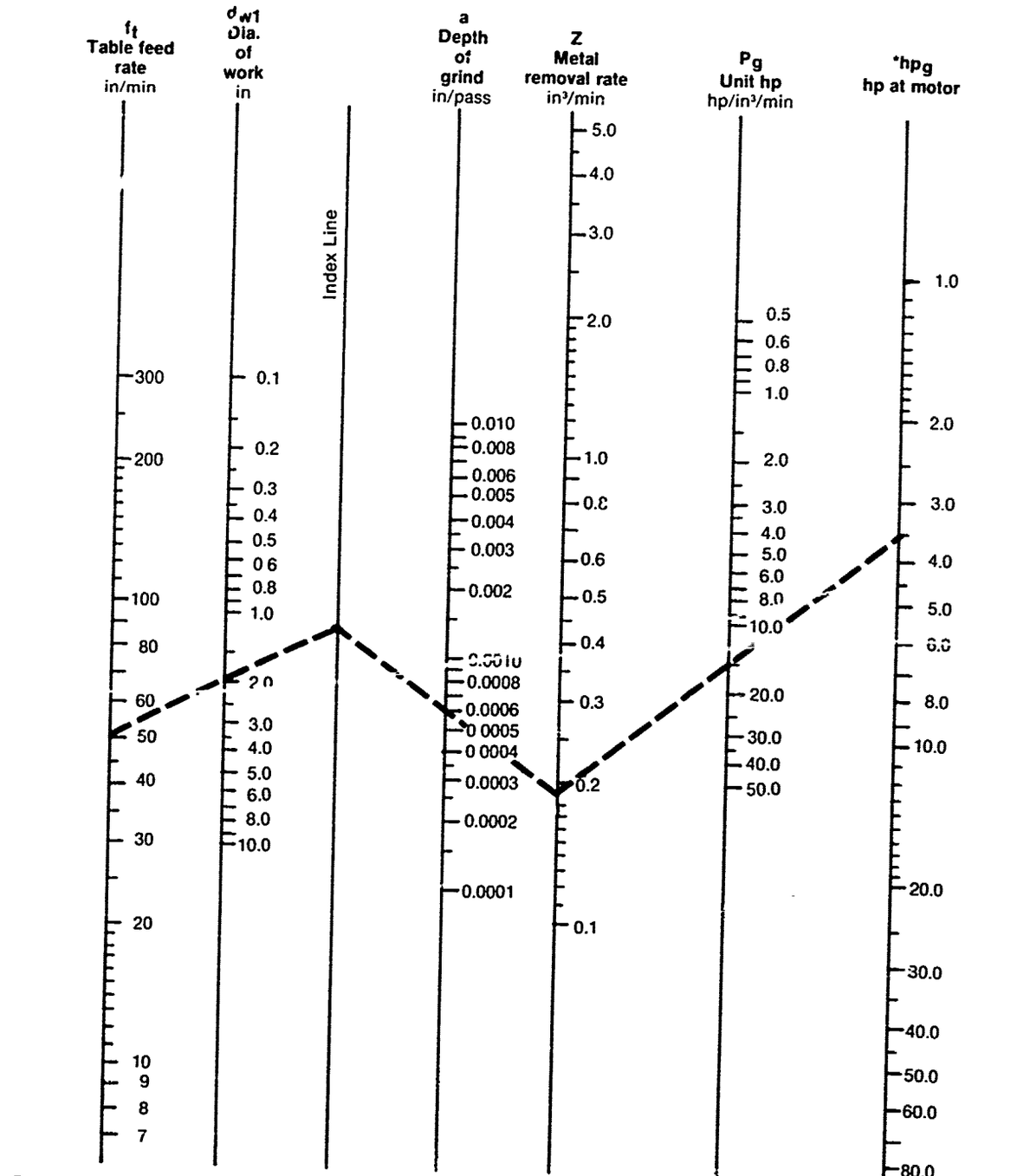
$Z = f_t \times b_w \times a$ (Vert. spindle)

$$hp_g = \frac{P_g \times Z}{E}$$

*hp_g = Horsepower at spindle motor for 80% spindle drive efficiency

Figure 20.4–5 Alignment chart for determining metal removal rate and horsepower required at motor: plunge grinding (reciprocating table) for horizontal and vertical spindle surface grinding.

20.4 Grinding Formulas and Charts



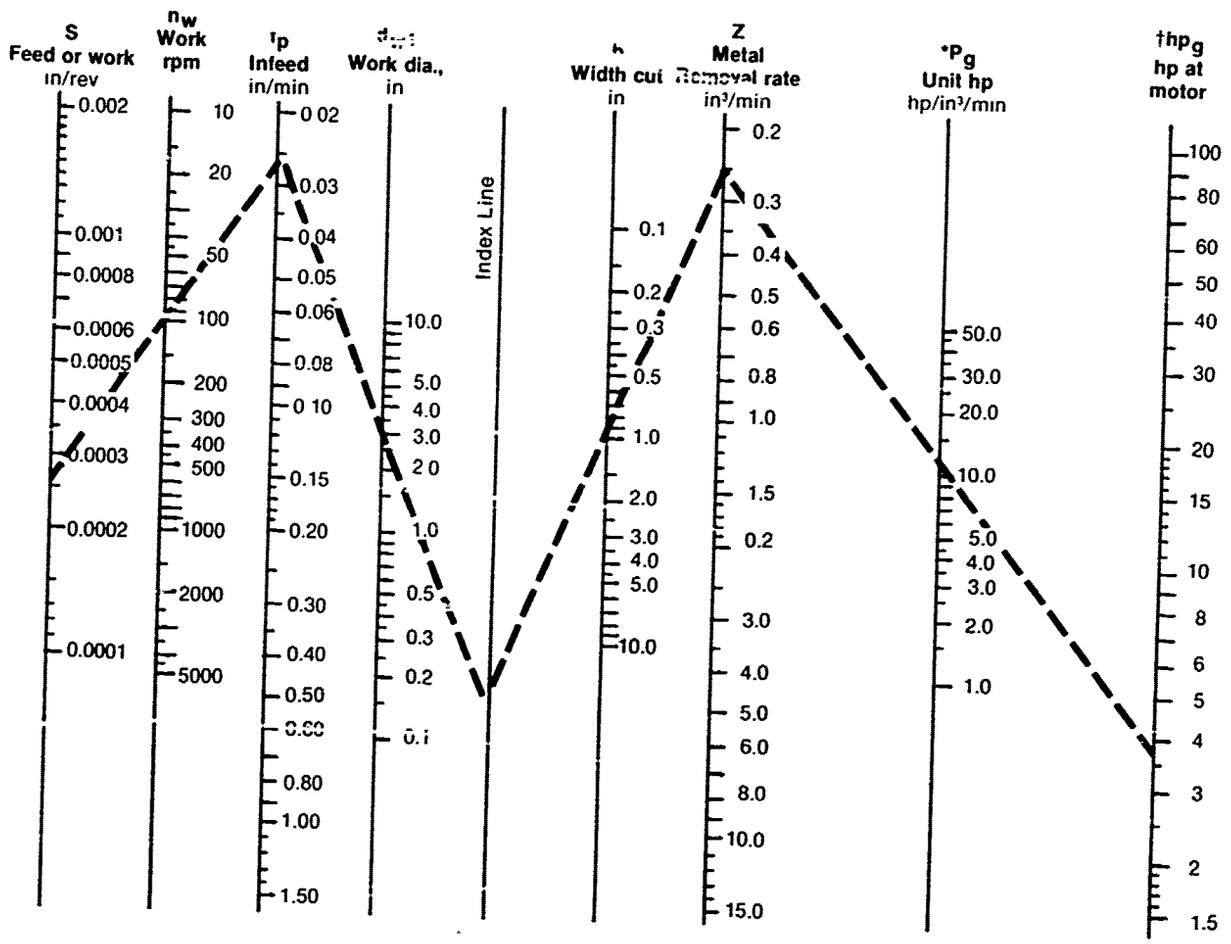
Example: Centertype cylindrical — Traverse grinding
8620 steel, 170 Bhn
Given: f_t = 50 in/min d_{w1} = 2 in a = 0.0006 in/pass
P_g = 15 hp/in³/min
Then: Z = 0.188 in³/min hp_g = 3.5 hp

Traverse grinding: $Z = \pi \times a \times f_t \times d_{w1}$

$$hp_g = \frac{P_g \times Z}{E}$$

*hp_g = Horsepower at spindle motor for 80% spindle drive efficiency

Figure 20.4–6 Alignment chart for determining metal removal rate and horsepower required at motor: traverse grinding for centertype cylindrical, centerless and internal grinding.



Example: Centertype cylindrical — Plunge grinding

4145 steel, 316 Bhn

Given: S = 0.00025 in/rev n_w = 100 rpm d_{w1} = 3 in

b = 1 in P_g = 11.6 hp/in³/min

Then: fp = 0.026 in/min Z = 0.25 in³/min hp_g = 3.6 hp

Plunge grinding: $Z = \pi \times b \times f_p \times d_{w1}$

$$hp_g = \frac{P_g \times Z}{E}$$

*See figure 20.4-3 for unit power values for centertype cylindrical grinding

†hp_g = Horsepower at spindle motor for 85% spindle drive efficiency

Figure 20.4–7 Alignment chart for determining metal removal rate and horsepower required at motor: plunge grinding for centertype cylindrical, centerless and internal grinding.

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Grinding has traditionally been used to provide final workpiece finish and dimensional accuracy. About 1962, the term "abrasive machining" appeared in the literature to cover those grinding operations used for stock removal as well as for the production of the final finish and accuracy.

There are various types of abrasive grinding operations; the prominent ones are described below.

VERTICAL SPINDLE, ROTARY TABLE SURFACE GRINDING

Vertical spindle surface grinding has been employed for many years as a stock removal operation on many common commercial alloys. It has been used in the automotive industry for grinding cast iron and steel components in lieu of milling. The normal stock removal of 0.125 to 0.250 inch (3.2 to 6.4 mm) on castings and forgings has been accomplished on parts which have essentially flat, unencumbered surfaces. In recent years, there has been an extension of the application of vertical spindle surface grinding to many larger parts, including machine tool beds and tables, cylinder heads, gear housings, motor cases, etc. Machines are being built with table sizes up to 14-foot (4 m) diameter and up to 300 horsepower (225 kW). It may be advantageous to redesign parts to take advantage of the benefits of this operation.

The recommended grinding conditions for this operation are contained in section 8.4, where it may be noted that wheel speeds in most common use vary between 3,400 and 5,000 feet per minute (17 and 25 m/s).

RECIPROCATING TABLE SURFACE GRINDING

Abrasive grinding is being applied for heavy stock removal using reciprocating table machines with both vertical and horizontal grinding wheel spindles. The application of the horizontal spindle, reciprocating table abrasive grinding is being augmented by the application of crush dressing to the grinding wheel, which minimizes idle time in the grinding operation. Data for surface grinding with horizontal spindle, reciprocating table machines are given in section 8.1. Horizontal spindle, reciprocating table surface grinding competes with milling on certain metals such as high temperature alloys which are extremely difficult to mill.

ABRASIVE BELT MACHINING

The Process

Abrasive belt machining, once confined to polishing and minor metal removal, has become a high-metal-removal-rate process. The advent of stronger and sharper grains, better bonds, and stronger belts accounts in part for the increasing popularity of abrasive belt machining. It can take the place of conventional grinding, polishing and similar operations. For high production, one machine can be equipped with several heads, each with a different belt so that roughing and finishing can be performed in one pass. This reduces floor space and capital investment requirements. Further economies may result from the use of worn, coarse-grain belts for finishing passes.

The Abrasive Belt Machine

Machines used for belt grinding have two common features: all are very rigid and all utilize high horsepower. Rigidity is at least as important as horsepower in obtaining good abrasive economies. The common types of machines in belt machining are centerless belt grinder, surface belt grinder, cylindrical belt grinder, and roll belt grinder.

The Abrasive Belt

Grinding belts used for abrasive machining are resin bond coated with either aluminum oxide, silicon carbide, or diamond grains. The grain is electrostatically coated to the belt in order to control orientation, dispersal and thickness. There is up to three times more chip clearance in a coarse grinding belt than in a comparable grinding wheel. This permits high metal removal rates at low pressures. Most failures of belts are caused by loading, glazing and stripping (shedding) which are discussed as follows:

- Loading is the filling of areas between abrasive grains. The use of lubricants and a weaker bond can retard loading.
- Glazing is the dulling of the abrasive grains resulting from the use of strong bonds. It can be eliminated by changing to a weaker bond and using a more "aggressive" contact wheel.
- Stripping is the shedding or breaking away of the bond and grains from the belt backing. It can be corrected by changing to a bond that has greater adhesion.

Contact Wheels and Platens

When the correct contact wheel or platen is used behind the belt, belt sharpness and cutting efficiency are maintained by breakdown of the dulled abrasive grains, thus producing and thereby presenting sharp grains to the work during the useful life of the belt. Stock removal rates are approximately in direct proportion to the pressure applied, within the capabilities of the grain size and bond type used.

The ability of the contact wheel or platen to make the belt cut is termed "aggressiveness." For optimum stock removal, a hard rubber (90 durometer) contact wheel with 45° serrations, 0.25-inch (6.4 mm) land, and 0.50-inch (12.7 mm) wide grooves provides aggressive cutting action and sheds dulled abrasive grains from the belt to eliminate glazing. Hard contact wheels are used both for heavy stock removal and for high accuracy. It is not uncommon to hold accuracy between ±0.0005 inch (±0.013 mm). Good abrasive belt operations consume only 4.5 to 7 horsepower per cubic inch per minute (0.20 to 0.32 kW/cm³/min) when grinding low carbon steel, compared to 6 to 10 horsepower per cubic inch per minute (0.27 to 0.46 kW/cm³/min) for comparable bonded wheel operations. Centerless belt grinding removal rates vary from 0.25 cubic inch per inch (0.16 cm³/mm) of belt width on small bars to 1 cubic inch per inch (0.65 cm³/mm) of belt width on larger bars. In

comparison, the new wide-wheel centerless grinders remove only 0.6 to 0.75 cubic inch per inch [0.39 to 0.48 cm^3/mm] width on large bars and require 8.3 horsepower per inch [6.2 kW] width of wheel compared to 7.5 horsepower per inch [5.6 kW] width for a belt

There are six types of belts as follows:

- Paper-backed with two glue coatings.
- Paper-backed with a glue making-coat and a heat-resistant resin sizing-coat.
- Cloth-backed with a glue making-coat and a heat-resistant resin sizing-coat.
- Cloth-backed with two resin coats.
- Cloth-backed, specially waterproofed with two resin coats.
- Belts containing dry lubricants.

Abrasive Belt Machining Conditions

Abrasive belt speeds range from 600 feet per minute [3 m/s] on certain ceramics to 14,000 feet per minute [70 m/s] on nonferrous snag grinding. Most abrasive machining is done between 2,500 and 5,500 feet per minute [13 and 28 m/s], with the most commonly used speed being 4,500 feet per minute [23 m/s]. Feeds vary from one inch per minute [25.4 mm/min] for heavy slabbing cuts to 240 feet per minute [73 m/min] for precision centerless belt grinding applications.

HIGH-EFFICIENCY OR HIGH-SPEED GRINDING

The name high-efficiency grinding is being used for abrasive machining employing very high grinding wheel speeds. Wheel speeds of 12,000 to 18,000 feet per minute [60 to 90 m/s] are being used today. By using high wheel speeds, it has been found that the rate of metal removal can be increased.

Types of High-Efficiency Grinding Machines

Shoe-Type Centerless Grinders – These appear to be the most numerous machines in production today and are used primarily for abrasive grinding of bearing races.

Cylindrical Plunge Grinders – There are many of these machines out in the field for grinding of pinion gears, cam shafts, steering knuckles and other components as will be described below.

Internal Grinders – These machines are being used primarily for the grinding of bearing races.

Surface Grinders and Centers Grinders – Development work on the high spindle speed application of these grinders is under way, but few of these grinders are being used in production.

Machine Design Considerations

Grinding machines designed for high-efficiency grinding require special considerations which prohibit the conversion of existing grinders into high-efficiency grinders. The design requirements for high-efficiency grinders include the following:

- High spindle speeds to provide grinding wheel speeds of 12,000 to 18,000 feet per minute [60 to 90 m/s].
- High work speeds, at least double that of normal grinders.
- High horsepower to accommodate the high rates of metal removal.
- High rigidity and freedom from vibration.
- Automatic wheel balancing on the spindle to minimize grinding wheel vibration
- Provision for the safety of the operator, the passerby and the machine tool, including use of special guard systems to contain the wheel in case of wheel breakage.
- Special coolant application systems to ensure that the grinding fluid reaches the grinding zone at the high wheel speeds.
- Filtration systems to remove the large quantities of swarf from the coolant system.
- Cooling systems to prevent overheating of the grinding fluid.
- The use of live centers rather than dead centers for cylindrical grinders to accommodate the increased work speed.

Grinding Wheels

Special grinding wheels have to be designed to withstand the high wheel speeds. Some of the design requirements include the following:

- Providing a composite wheel with a hard, fine section toward the center, or a single-graded wheel impregnated with resinoid in the center section for added strength.
- Wheel design involving clamping of wheel segments.

Grinding Wheel Dressing

Diamond roll wheel dressing is being used to reduce the time for dressing the wheel.

Types of Materials and Components

Low carbon carburizing steel: stems of gears
Medium carbon alloy steel: steering knuckles, gear stems, Universal spiders
Bearing steels–hardened: bearing races
Cast iron: crankshafts, slip yoke

Applications

Most of the high-efficiency cylindrical grinding applications are plunge grinding operations. Cylindrical plunge grinding may economically replace turning under the following conditions where:

- The product of the diameter times the length of the grind is greater than 4.
- The ground length does not usually exceed 7 inches [178 mm].
- The stock removal is limited to about 0.25 inch [6.4 mm] on the diameter.
- The tolerance is less than ±0.003 inch [±0.075 mm].
- Special problems (for example, interrupted cuts) which might be more restrictive on turning than on grinding.
- The surface roughness is 30 microinches R_a [0.76 μm] or greater.
- The workpieces are mass produced, are manufactured in large batches, or are similar parts produced in short runs.

Table 20.5-1 illustrates some workpieces which were successfully high-efficiency machined and compares them with the above list of economic guidelines.

CYLINDRICAL CRUSH DRESS GRINDING

A recent addition to abrasive machining has been the design of cylindrical grinders for removing large amounts of stock by plunge grinding both straight and formed parts. The grinding wheels are crush dressed. The width of the wheel or the length of the ground workpiece can be as much as 12 inches [305 mm]. A necessary requirement for this grinding system includes a high pressure coolant jet spray which is traversed back and forth across the grinding wheel. This jet spray blasts metal and swarf loose from the grinding wheel and maintains a clean wheel. This method of grinding is being used on steels and high temperature alloys. It is being applied to the grinding of jet engine components and mechanical test specimens instead of turning and finish grinding.

CREEP FEED GRINDING

Creep feed grinding is a process whereby the grinding wheel takes the full depth of cut in a single pass at an extremely slow feed rate. This process was developed in Europe some twenty years ago but did not gain wide acceptance until recently when specially designed grinding machines with high stability, increased power and improved drive systems became available. With such machines it is possible to remove as much as 1 inch [25 mm] of metal from flat or cylindrical surfaces in a single pass, which rivals the capacity of milling machines.

Metal removal rates as high as 1 cubic inch per second [16.4 cm^3/s] with wheel speeds of 20,000 feet per minute [102 m/s] have been reported.

With the present state of the art, it is imperative that the process parameters be evaluated for each new application. This is especially true if the surface integrity of the part is a consideration.

TABLE 20.5-1 Mass Production Applications of High-Efficiency Grinding

WORKPIECE	MATERIAL	CRITICAL TOLERANCE	PRODUCT OF d x L	DEPTH OF STOCK (on diameter) inch	SURFACE ROUGHNESS μin R_a
Stem pinion	8620	± 00025 or ±.0015	7.5	varied 1/8 to 1	none
Slip yoke	Cast iron	±.0005	5.6 to 9.0	3/8	15 to 30 or 30 to 60
Steering knuckle	Steel	±.0035	5.5	1/4	none
Sun gear	Steel	±.001	7	3/8	none
Universal spider	Steel	±.001	4.3	1/4	63 max.
Compressor cage	Cast iron	±.00075	25	1/4	40 max.
Crankshaft	Cast iron	±.0005	4.5	1/4	50 max.

SOURCE: C. B. Matson, High effiency centertype grinding, Technical paper MR71-147, Society of Manufacturing Engineers, Dearborn, MI, 1971.

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SECTION 21

ECONOMICS IN MACHINING AND GRINDING

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Effect of Surface Roughness and Dimensional Tolerance on Cost 21-3
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ECONOMICS IN MACHINING AND GRINDING 21

INTRODUCTION

The annual labor and overhead cost for operating metalcutting machine tools in the United States has been estimated to be approximately $115 billion, as shown in table 21-1. The total shipments of metalcutting machinery in the United States have exceeded $2 billion per year, and in 1979 almost $2 billion was spent for small cutting tools. From these data, it is obvious that metalcutting is an enormous industry in the U.S.A. and that even a modest reduction in the cost of operating machine tools could very well result in nationwide savings of billions of dollars per year. It is apparent that similarly high proportionate savings also can be achieved by individual companies in industry.

TABLE 21-1 Estimated Annual Labor and Overhead Cost for Operating Metalcutting Machine Tools in Industries in the United States

Total number of metalcutting machine tools	= 2,301,500*
Average labor + overhead cost	= $25 per hour
Average working day	= 8 hours
Number of working days per year	= 250
Average number of direct labor personnel per machine	= 1
Total cost of labor + overhead: 2,301,500 x $25 x 8 x 250 x 1	= $115,075,000,000

It appears reasonable to conclude that the cost of labor + overhead for machining required for manufacturing in the U.S.A. is of the order of:

$115,000,000,000 Annually

*Based on *12th American Machinist Inventory* (1976-1978). (See summary in *American Machinist*, December 1978, p. 133-148.)

There are two general approaches for studying the cost of machining in metalcutting plants. The first is to examine the subject in a general or qualitative way, and the second is to make a quantitative analysis of cost and production rate. Both of these approaches are discussed in this section.

EFFECT OF ENGINEERING DESIGN ON COST

When examining costs in a qualitative way, it should be pointed out that the basic cost in machining a component is determined by the design of the component. The basic cost in machining is first determined by the material selected for the part, that is, by the material per se, its heat treatment, and resultant metallurgical condition and hardness. Figure 21-1 indicates the relative cost of machining a given component made from a wide variety of alloys. Based upon a part cost of $10 for turning 7075-T6 aluminum alloy, it can be seen that turning 1020 steel would cost $25, turning 4340 steel, quenched and tempered to 52 R_C, would cost $100, and turning Inconel 700 would cost over $300. A detailed table of the relative time for machining the same group of alloys using various machining operations and tool materials is given in table 21-2.

The basic cost of machining also is determined by the size, [illegible] and geometry of the component. A rigid part with [illegible] surfaces can obviously be machined quicker and at lower costs than a flimsy part with complex surfaces. In addition, the engineering design specifications for accuracy and surface roughness play a major role in determining the machining cost.

EFFECT OF SURFACE ROUGHNESS AND DIMENSIONAL TOLERANCE ON COST

The relative cost of machining is closely associated with both dimensional tolerance and surface roughness. The percentage machining cost in machining steel parts is exemplified in figure 21-2. As the surface roughness requirement becomes more stringent, the cost increases because more than one cut on a given machine tool is required to achieve that level of roughness. For example, a surface might have to be rough turned, then semi-finish turned, then finally finish turned to achieve the required surface roughness. The surface roughness specification may be even finer than that readily obtained by a chip removal process, and in this case, a second operation such as grinding or even a third operation such as honing may be required to achieve the surface roughness as well as the dimensional accuracy. Figure 21-2 illustrates the great increase in cost that occurs in order to achieve the desired finer surface roughnesses.

The overall machining costs also are associated with dimensional tolerance. As a matte. of fact, close tolerance requirements usually dictate finer surface roughnesses. The interrelationship of dimensional tolerances, surface roughness, and their effect on machining costs are illustrated in the charts of figure 21-3.

MACHINING COST AND PRODUCTION RATE

It is possible to quantitatively determine the cost and production rate for a given machining operation on a specific work material. Equations have been developed to determine the cost per piece and the production rate in pieces per hour for specific machining operations. The total cost for machining comprises costs associated with operating the machine tool and costs associated with the cutter and its reconditioning. The machine tool cost can be broken down into idle cost, tool reconditioning cost, and feed or cutting cost. The idle cost, which consists of rapid traverse, load and unload, and tool change costs, remains constant with change in cutting speed, while the feed or cutting cost decreases with increasing cutting speed. The tool reconditioning cost generally increases with increasing cutting speed because greater cutter wear rate is associated with the higher speeds. The total cost is the sum of all of the above cost elements. This total cost is seen to go through a minimum at some intermediate cutting speed and then sharply increase. The production rate in pieces per hour increases with increasing cutting speed, goes through a maximum and then decreases. Curves demonstrating these relationships of machining cost and production rate to cutting speed are contained in figure 21-4.

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Although the previous discussion has centered on the relationship of cost to cutting speed, it should be pointed out that cost also is a function of other machining parameters, such as feed, depth of cut, width of cut, tool material, cutting fluid, etc

PROCEDURE FOR CALCULATING COST AND PRODUCTION RATE

The following steps describe a method for calculating machining cost and production rate.

1. Machining Data and Machining Parameters

Data relating the tool life to machining parameters must be obtained for those work materials that are to be machined. Data can be obtained from handbooks and may also be obtained from historical shop experiences. It is important to have a well-defined format for recording and storing significant data. Typical data formats for turning, milling, drilling, reaming and tapping are shown in tables 21-3 through 21-5.

2. Cost and Production Rate Equations

Equations for determining costs, operating times, and production rates for various machining operations are listed in tables 21-6 and 21-8 for English units and tables 21-7 and 21-9 for metric units. The first bracket of terms in the cost equations determines the time and cost for the machine tool, and the second bracket of terms determines the cost for the cutter and its reconditioning. In tables 21-6 and 21-7, the cost equations are given for turning, milling, drilling or reaming, tapping, and center drilling or chamfering. These equations apply to both conventional and numerical control machine tools. It should be noted that a separate equation is provided for calculating the handling and setup costs. In the case of conventional machining, the two terms in this equation should be added into the appropriate operation equation in order to calculate the handling and setup costs of a specific operation such as turning or milling, etc. In the case of NC machining, the individual equations are used for each machining operation in sequence, while the handling and setup equation is used separately, as will be illustrated in an example to follow. The equations for determining the operating time and the production rate for each operation are given in tables 21-8 and 21-9. It is desirable to program all of the cost and production rate equations on a computer for ease of calculations.

3. Supporting Data Required to Complete Calculations

In addition to tool life data, time study data and tool cost data are required for a cost and production rate determination. Tables 21-10 and 21-11 list and define the variable factors that appear in the cost and production rate equations. Figure 21-5 illustrates the setup factors for various machining operations. Note that "R" equals the total rapid traverse distance for a tool or cutter in one operation, whereas "e" equals the extra travel in feed.

The derivation of the terms in the cost equations for turning and milling are given in table 21-12.

The procedure described above has been applied in several situations to generate the examples that follow.

Examples

1. Example of a Cost and Production Rate Determination in Turning on a Conventional Engine Lathe

Table 21-13 contains the time study and cost data for turning a shaft 3.5 inches in diameter by 19 inches long on a conventional engine lathe. The material was 4340 steel, quenched and tempered to 300 Bhn. Three types of tools (that is, brazed carbide, throwaway carbide, and high speed steel) were used for the cost investigation. The tool life data are given in table 21-14. The tool life versus cutting speed data sets are denoted by the circled numbers 1, 2, 3, and 4 for the C-7 carbide tool material, and 5, 6, 7, and 8 for the high speed steel tool material.

The lathe tool setup for turning using the brazed carbide, the throwaway carbide and the solid high speed steel tools was the same as that illustrated in figure 21-5.

Using the above data and the equations for turning from tables 21-6 and 21-8, the machining cost and production rate were determined. The calculations were performed on an IBM 1130 computer, and a printout of the results is shown in figure 21-6. It should be noted that there are three sets of calculations: one for brazed carbide tools, one for throwaway carbide tools, and one for solid high speed steel tools. Using the tool life data for the C-7 carbide tool material and the time study data for brazed carbide tools, cost calculations were made at each of four cutting speeds.

Notice that the printout contains not only the total cost per piece and the production rate in pieces per hour but also all the cost factors that make up the total cost. In the case of the brazed carbide tool, there were ten cost factors; for the throwaway carbide tools, seven; and for the solid high speed steel, eight. A quick glance at the cost factors in figure 21-6 indicates which are significant and which are insignificant. For example, with the brazed carbide tool, when cutting at 470 feet per minute, the total cost was $5.33 per piece. Of this, the feeding cost was $1.50, the load and unload cost $0.92, the setup cost $0.42, the tool change cost $0.49, and the tool sharpening cost $1.48. The less significant factors were as follows: rapid traverse cost $0.11, tool depreciation cost $0.13, rebrazing cost $0.16, tip cost $0.10, and the grinding wheel cost $0.02.

For the throwaway carbide tools, figure 21-6, it can be seen that all the tool costs were virtually nil. On the other hand, when turning with solid high speed steel, the tool cost was an appreciable portion of the total cost. Thus, when turning with high speed steel at 45 feet per minute, the total cost was $21.29 per piece, the tool change cost was $1.29, and the tool sharpening cost $2.58.

The cost and production rates for turning 4340 steel at 300 Bhn were plotted against cutting speed. Figure 21-7 contains these plots for brazed carbide, throwaway carbide and high speed steel tools. The data show that the cost per piece decreased as the cutting speed increased when using throwaway carbide tools. The cost per piece was at a minimum at approximately 360 feet per minute for the brazed carbide, and the cost per piece was at a minimum at approximately 60 feet per minute for the high speed steel.

The minimum costs for turning within the range of experimental data were about $3.09 with the throwaway carbide, $4 44 with the brazed carbide and $18.62 with the high speed steel. The maximum production rate, also within the range of experimental data, was 8 pieces per hour for the throwaway carbide tools, 7 pieces per hour with the brazed carbide tools, and 1.8 pieces per hour with the high speed steel tools.

For those who would like to calculate the cost manually, the cost calculations for the example just described are given in table 21-15 for turning with the brazed carbide tool.

2. Example of a Cost and Production Rate Determination in Face Milling on a Conventional Milling Machine

Table 21-16 contains the time study and cost data for face milling a block 2 inches wide by 8 inches long. The work material was 4340 steel, quenched and tempered to 341 Bhn. A two-inch wide cut was taken on the eight-inch long workpiece with 4-inch diameter milling cutters. A solid high speed steel cutter and two types of carbide cutters (inserted tooth and throwaway insert) were used. The setup used for this example was the same as that for milling illustrated in figure 21-5.

The tool life data for the alloy are given in table 21-17. In this table, the sets of data relating tool life in inches per tooth to cutting speed in feet per minute for the alloy are identified by the circled numbers 1 through 6.

The IBM 1130 computer was used to calculate the cost per piece using the milling equation from table 21-6 and the production rate using the milling equation from table 21-8. The computer printout of the results is shown in figure 21-8.

Examination of the computer printout reveals the significant cost factors and the comparative costs per piece and production rates among the types of tools used. For instance, the printout shows that the use of a throwaway carbide cutter resulted in higher production and lower costs. This is more evident from examining figure 21-9, which indicates that the cost per piece in face milling the 4340 steel did not vary as sharply for the throwaway carbide cutter as it did for the other cutters. The production rate curve for the throwaway cutter lies above the other two types. Of specific interest is that for the data used in this example, the mimimum cost and maximum production rate occurred for the case of throwaway carbide cutters at 550 feet per minute.

3. Example of a Cost and Production Rate Determination in Drilling Using a Conventional Drill

Table 21-18 contains the time study and cost data for drilling holes in 4340 steel, annealed to 212 Bhn. High speed steel drills were used to drill five holes, one-half-inch deep in each part. The drill diameter used was one-quarter inch. The geometric setup used was the same as that illustrated for drilling in figure 21-5.

The tool life data is listed in table 21-19. The sets of data giving the drill life in number of holes are identified by the circled numbers 1 through 8. The cost and production equations required that the drill life (T_t) be expressed in inches. Therefore, it was necessary to multiply the drill life, in number of holes drilled, by the hole length to get the drill life in inches of travel required to dull the drill. Using data set 1, the drill life was 30 holes. The length of each hole was 0 5 inch. Therefore, the drill life was T_t = 15 inches (30 x 0.5 inch).

Figure 21-10 is the computer printout of the results from using the drilling equation from table 21-6 to calculate the cost per piece and the drilling equation from table 21-8 to determine the production rate.

Figure 21-11 shows the cost and production rate curves for this drilling operation. The data show that the 0.005 inch per revolution feed can achieve higher production rates and lower costs than the 0.002 inch per revolution feed, provided that proper cutting speeds are used.

4. Example of Machining a Part on an NC Machining Center

An example of a 4340 steel forging machined on an NC machining center is shown in figure 21-12. The operations were to face mill the top surface, peripheral end mill the sides and ends, mill two slots and drill two holes. The time study and tool cost data are given in table 21-20, and the pertinent machining parameter and tool life data for the various operations are given in table 21-21. The cost and production rates for the individual operations were calculated on the computer and a printout is given in figure 21-13. Again, the computer prints not only the total cost but also the individual cost factors. It should be noted that calculations were made for each of the individual operations, and for each operation a line of data shows the cost corresponding to the feed, speed and tool life combination. The minimum cost for each of the operations in the printout of figure 21-13 is circled, and a summary of the best machining conditions is given in figure 21-14.

DETERMINING OPTIMUM CUTTING CONDITIONS

As shown in the previous examples, there are cases where the optimum cutting conditions lie beyond the available data. In order to optimize, it is necessary to determine the mathematical relationship between tool life and the pertinent cutting parameters such as speed, feed, and depth and width of cut. Probably the most common approach is to assume that Taylor's equation relating tool life to cutting speed applies:

for turning

$$vT^n = S$$

for milling, drilling, reaming and tapping

$$vT_t^n = S_t$$

where:

v	=	cutting speed
T and T_t	=	tool life
S and S_t	=	reference cutting speed
n	=	tool life exponent

(See table 21-10 or 21-11 for detailed definition of variables.)

With these Taylor equations, the cost for the various machining operations can be minimized. This has been done by substituting the appropriate Taylor equation into the cost equation, differentiating the cost with respect to cutting speed, and setting the derivative equal to zero. The cutting speed calculations for minimum cost ($v_{min\ cost}$) and for maximum production ($v_{max\ prod}$) for the conventional as well as the NC machining operations are given in the equations in tables 21-22 and 21-23. The corresponding tool life equations for minimum cost and maximum production are given in table 21-24. The values of $v_{min\ cost}$ and $v_{max\ prod}$ in the denominators must be calculated using the appropriate equation(s) from table 21-22 or 21-23.

The validity of the optimized determination depends, in turn, on the validity of the constants n and S or S_t in the Taylor equation. The most accurate values of these constants can be determined by actual experimentation (that is, by actual cutting tests). In so doing, it is also possible to determine the range of cutting conditions over which the Taylor equation applies. The least reliable procedure is to pick an average value for the Taylor constant from a handbook. It is suggested that if one assumes the Taylor relationship and proceeds to determine optimum cutting conditions, these conditions should be verified by actual shop tests.

The relationship of cutting conditions to tool life as determined by actual cutting tests may be too complex to be represented by the simple Taylor equation. Techniques are now available to mathematically model the more complex relationship of tool life to cutting speed, feed, and depth of cut. The mathematical model can, in turn, be used to determine cost and production rate over the wide range of machining conditions with subsequent determination of minimum cost, minimum cutting time and maximum production rates. These techniques are too complex for inclusion in this handbook.

SHOP PROCEDURES FOR OPTIMIZATION OF MACHINING CONDITIONS

When it is felt necessary to decrease cost or increase productivity of a machining operation, it is possible to experiment on the shop floor by changing machining conditions. It is necessary to keep careful records of the changes in cutting conditions and the effect of these changes on tool life as well as on production rates.

The first step is usually to increase the feed. The feed may be increased until either the specified surface roughness is no longer obtained or the tool life starts to decrease. With the best feed, the next step is to increase and then decrease the cutting speed and observe the change in tool life. By this manner, the combination of feed and speed can be selected to achieve maximum productivity. Additional factors which may be investigated for their effect on tool life include cutting tool material, tool geometry, and cutting fluid.

Although the feed rate as a result of shop trials can be readily observed, it is not possible to directly observe the effect of these trials on the overall machining cost since the machining cost involves not only machine tool time but also the cutter cost. It is necessary, therefore, to calculate the overall machining cost and production rate as a function of the machining parameters using the procedure outlined previously.

TECHNIQUE FOR CALCULATING COST AND PRODUCTION RATE

Although the equations used for the cost and production rate calculations involve only simple mathematics, the detailed analysis of a given machining setup will become very time consuming because many factors must be included. With this in mind, techniques have been developed that allow the rapid analysis of a machining operation through the use of computers and programmable calculators.

The cost and production rate equations given in tables 21-6 and 21-8 have been programmed in FORTRAN IV for use on a computer with as little as 8K memory, such as an IBM 1130. This program, called NCECO, is available through the Machinability Data Center and is supplied in card-deck form and includes full documentation. With minor modifications for input-output, this program will operate on any digital computer supporting the FORTRAN IV language. The program will accept any combination of machining operations required for a part setup including: turning, face milling, end milling, drilling, reaming, tapping, center drilling and chamfering. Capability exists to determine the effects of using all types of tools, that is, high speed steel, brazed carbide, or throwaway carbide. To run this program, data such as that in table 21-13 is compiled for the machining operation. These data are then punched on cards which are input to the computer. The computer then prints out a detailed cost breakdown such as that shown in figure 21-13.

With the advent of programmable calculators, it is now possible to perform these calculations quickly without utilizing a large computer. A calculator generally uses semiconductor electronics that allow the solving of a mathematical problem using a series of keystrokes on the machine. A programmable calculator has the ability to store and automatically execute the series of keystrokes necessary to solve a particular problem. Using this feature, a programmable calculator can be instructed to perform all the calculations necessary for cost and production rate analysis with the user supplying only the data necessary for the calculations. Two such programmable calculators are the Hewlett-Packard HP-67 and the Texas Instrument TI-59.

The Hewlett-Packard HP-67 is a pocket-sized programmable calculator powered by alternating current or rechargeable batteries. All output is by digital display. The programs are stored on small magnetic strips and are read by the machine simply by inserting a strip in a slot on the side of the machine. The small memory size of this machine makes it necessary to use a separate memory strip for each type of machining operation. The magnetic strips are stored in a 3-by-5-inch card which gives all the necessary instructions for running a complete analysis. Since this calculator is pocket-sized, it is well suited for doing these calculations right on the shop floor. An enlarged version of the instructions and sample inputs and outputs are shown in figure 21-15.

The Texas Instruments TI-59 programmable calculator is similar to the Hewlett-Packard calculator. When attached to a TI-PC100A printer, cost and time analysis can be accomplished in an interactive mode. Instructions are printed out to the user describing the necessary inputs. The results of the calculations are also printed with appropriate labels. Also included is the capability to save the input data on magnetic strips for later analysis without having to re-input all the data by hand. An example of the cost and production time program run on the Texas Instruments TI-59 calculator with printer is shown in figure 21-16.

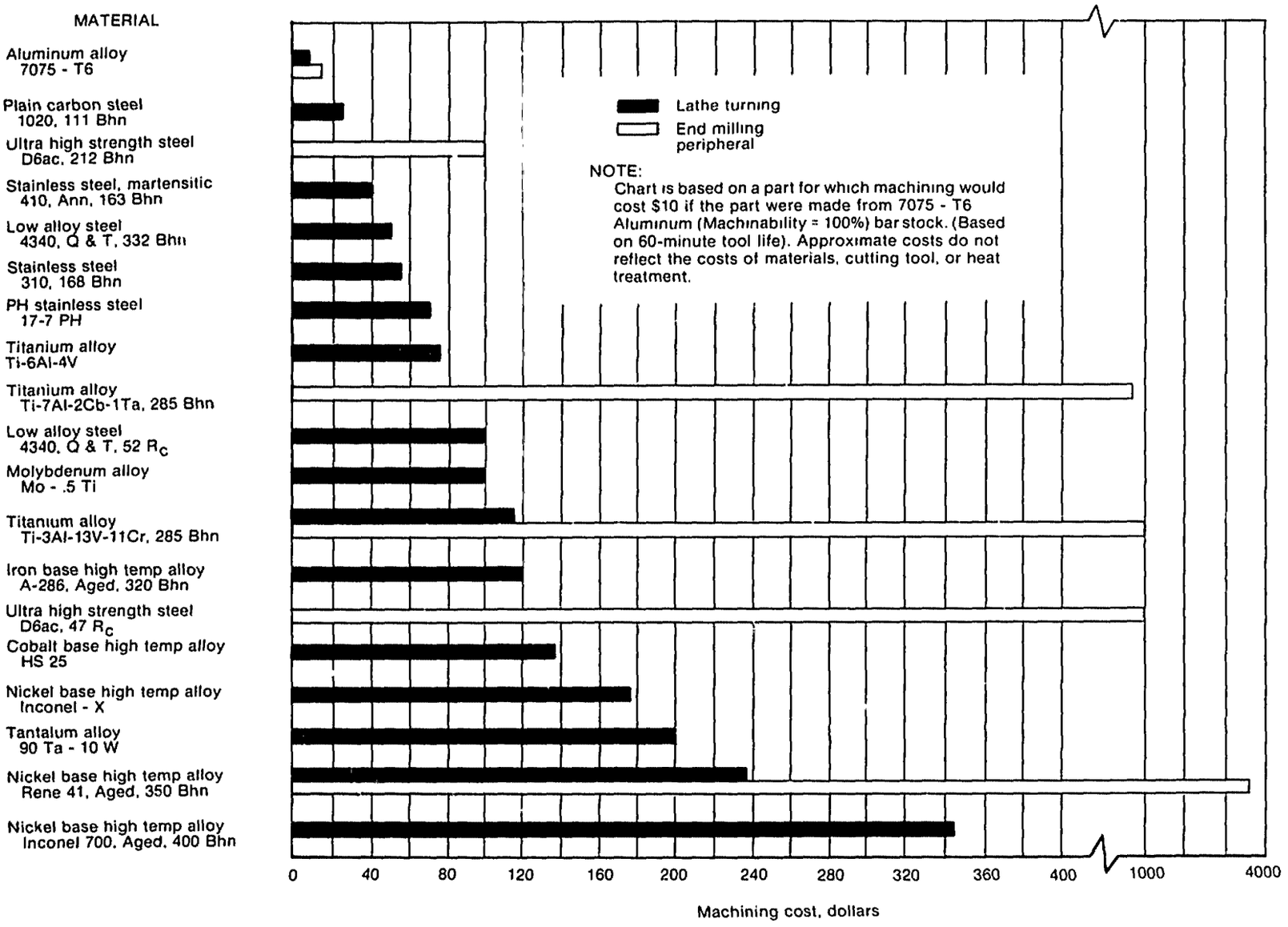


Figure 21–1 Relative machining costs for hard and soft aerospace materials. (Adapted from Profile milling requirements for the hard metals 1965–1970, Report of the Ad Hoc Machine Tool Advisory Committee to the Department of the Air Force, May 1965)

TABLE 21–2 Relative Machining Time of Various Alloys Compared to 4340 Steel, 300 Bhn

MATERIAL GROUP	MATERIAL	CONDITION*	HARDNESS Bhn	RELATIVE MACHINING TIME							
				Turning		Face Milling		End Milling		Drilling	Tapping
				HSS	Carbide	HSS	Carbide	HSS	Carbide	HSS	HSS
Alloy steels		Q & T	300	1 0	1.0	1 0	1.0	1.0	1.0	1.0	1.0
		Q & T	400	2.5	1.7	5.0	2 5	2.0	2 5	1.7	2 5
	4340	Q & T	500	3.3	3 3	10.0	3 3	5.0	10 0	5.0	5.0
		Q & T	520	5.0	5.0	25.0	10.0	7.0	11.1	10.0	10.0
		Ann	210	0 8	0.8	0 4	0.5	0.7	0.6	0.8	0.7
		Norm	320	1 3	1 0	1.7	1.7	1.0	1.0	1.0	1.0
High strength steels	D6ac	Ann	220	0.8	0.8	0.6	0.7	0.5	0.7	0.8	1.0
		Q & T	560	—	14.0	—	10.0	—	25.0	1.1‡	—
		Ann	200	0.8	0 9	0.5	0.5	0.9	1.0	0.8	1.3
	H11	Q & T	350	1.7	2.0	1.7	2 0	3.3	5.0	1.4	1.7
		Q & T	520	—	5 0	25.0	10.0	—	10.0	10.0	10.0
Maraging steels	200, 250, 300 Grades	Ann	320	1.7	0.8	1.0	1.4	0.9	0.9	0.9	1.3
		Mar	500	3 3	2.5	2.5	5.0	5.0	5.0	3.0	5 0
Stainless steels, austenitic	302, 304 317, 321	Ann	180	0.8	0.9	1.1	1.0	1.0	1.1	0.8	1.0
Stainless steels, martensitic	410, 420	Ann	180	0.9	0.8	0.8	0.7	1.4	0.8	0.7	0.8
		Q & T	300	1.7	1.3	2.0	2.0	1.7	1.3	0.8	1.3
	420	Q & T	400	2 5	3.3	5.0	5.0	3.3	5.0	1.7	2.5
Stainless steels, precipitation hardening	17-4 PH 17-7 PH	Ann	170	1.0	0.9	1.1	0.9	1.1	0.8	1.0	1.0
	AM-350	Ann	300	1.4	1.4	1.4	1.4	1.4	1.0	1.4	1.3
	17-4 PH 17-7 PH AM-350	Q & T	400	2 5	2 0	3.3	3.3	2.5	5.0	2.5	2.5
Titanium alloys	Ti-100A	—	175	0.7	0.7	0.8	1.4	0.4	0.8	0.5	0.8
	Ti-5Al-2.5Sn	Ann	300	1.4	1.4	1.4	2 5	0.5	1.3	0.7	1.0
	Ti-6Al-4V	Ann	310	1.7	2 0	2.0	3 3	1.0	2.0	1.2	1.3
		STA	365	2 0	2.5	2.0	3.3	2.0	2.0	1.7	1.7
	Ti-7Al-4Mo Ti-6Al-6V-2Sn Ti-8Al-1Mo-1V	Ann	320	2.0	2.0	2.5	2.0	1.1	1.7	0.9	1.4
	Ti-6Al-6V-2Sn Ti-7Al-4Mo	STA	420	2.5	3.3	2.5	5.0	1.4	2.5	1.4	2.5
	Ti-13V-11Cr-3Al	ST	310	2.5	5.0	3.3	3.3	2.0	3.3	3.3	2.5
		STA	400	2.5	5.0	3.3	10.0	3.3	4.0	10.0	3.3
High temperature alloys	Refle 41 Inconel 700 U-500	ST	280	5.0	5.0	10.0	16.7	5.0	5.0	3.3	2.5
		STA	365	10.0	5.0	10.0	16.7	10.0	12.5	10.0	5.0
Nickel base	Inconel 718	ST	270	5.0	5.0	3.3	10.0	3.3	10.0	3.3	2.5
		STA	370	5.0	5.0	5.0	10.0	12.5	12.5	5.0	5.0
Cobalt base	HS25	ST	200	3.3	5 0	5.0	10.0	5.0	5.0	3 3	2.5
	S-816	STA	300	5.0	10.0	10.0	12.5	10.0	10.0	5.0	3.3
Iron base	A-286	ST	200	1.7	2.5	1.4	3.3	2.0	3.3	1.7	1.7
	19-9DL	STA	300	2.0	3.3	3.3	5.0	3.3	12.5	3.3	2.5
Aluminum alloys	7075-T6	STA	75 to 150†	0.12	0.3	0.06	0.1	0.1	0.3	0.1	0.5

Source. R. L. Vaughn and N. Zlatin, "Producibility Aspects of Aerospace Products with Regard to Machinability," ASTME Paper WE S7-29, 1967.

*Condition: Ann—Annealed; Norm—Normalized; Mar—Maraged; Q & T—Quenched and Tempered; ST—Solution Treated; STA—Solution Treated and Aged

†Brinell Hardness for 500 kg load

‡Carbide Drill

21 ECONOMICS IN MACHINING AND GRINDING

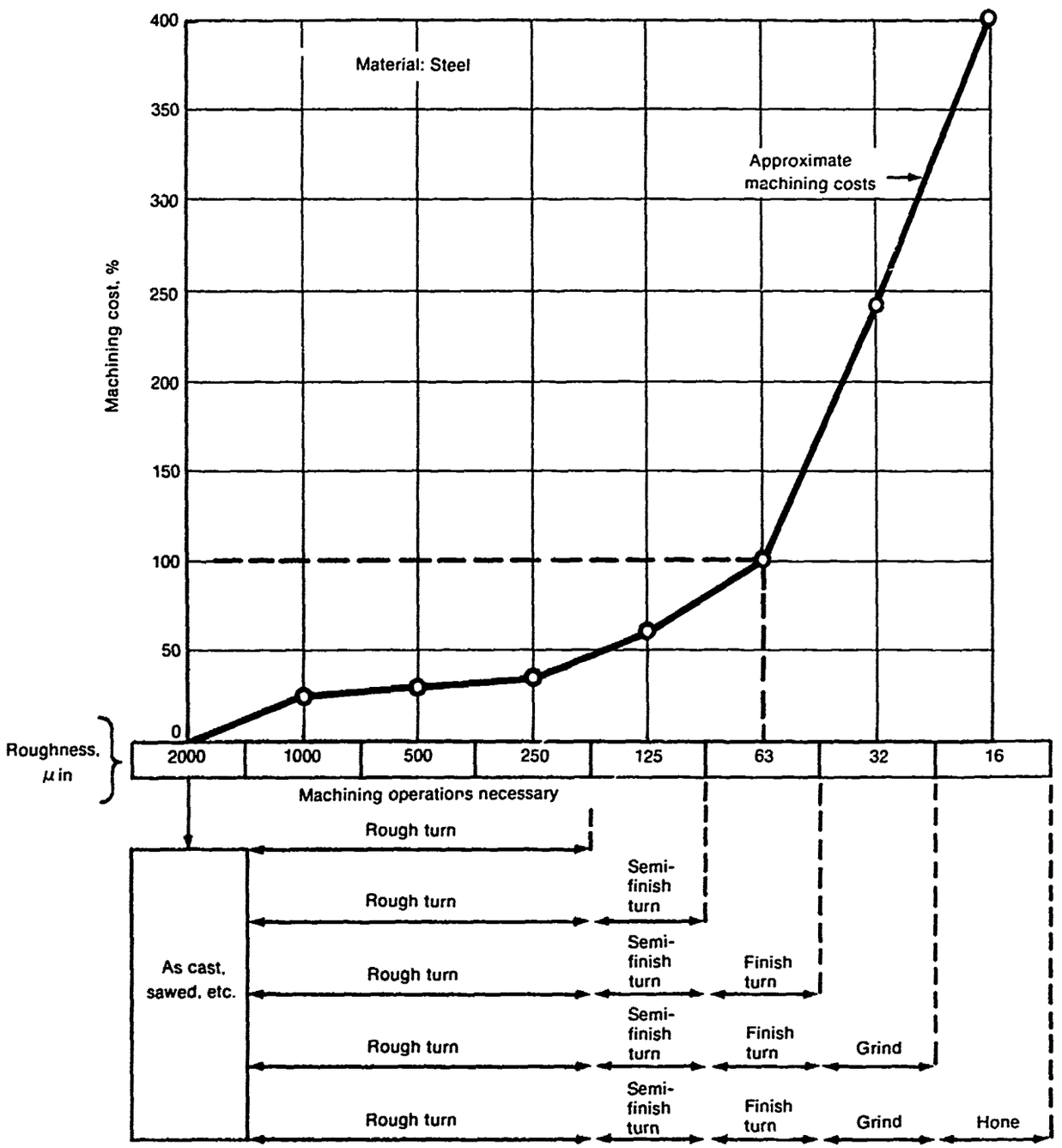


Figure 21-2 Relative machining costs and surface roughness for steel parts. (Courtesy of General Electric Company)

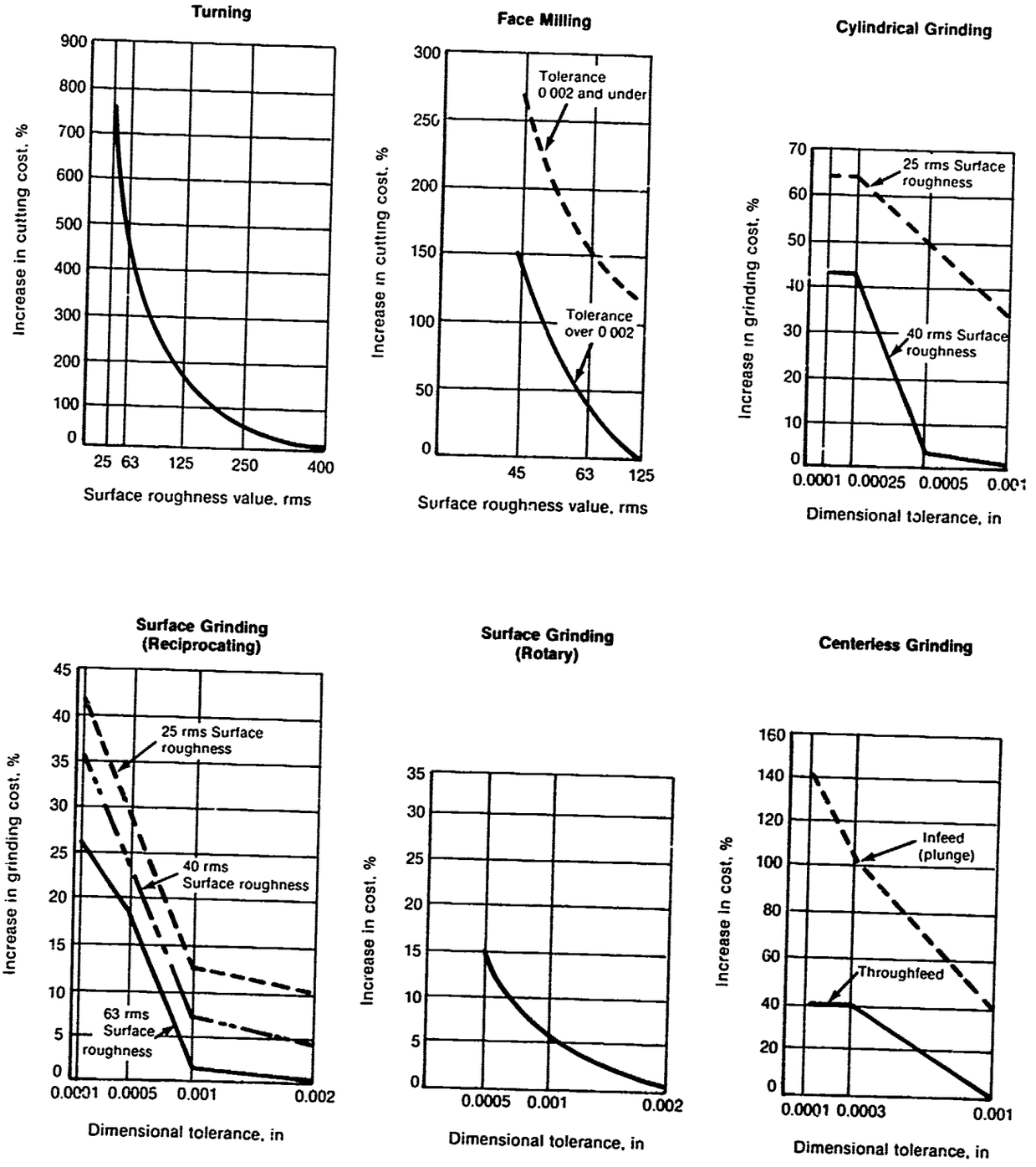


Figure 21–3 Effect of tolerance and surface roughness on machining costs for several operations. (L. J. Bayer, Analysis of manufacturing costs relative to product design, Paper No. 56-A-9, American Society of Mechanical Engineers, New York, NY, 1956)

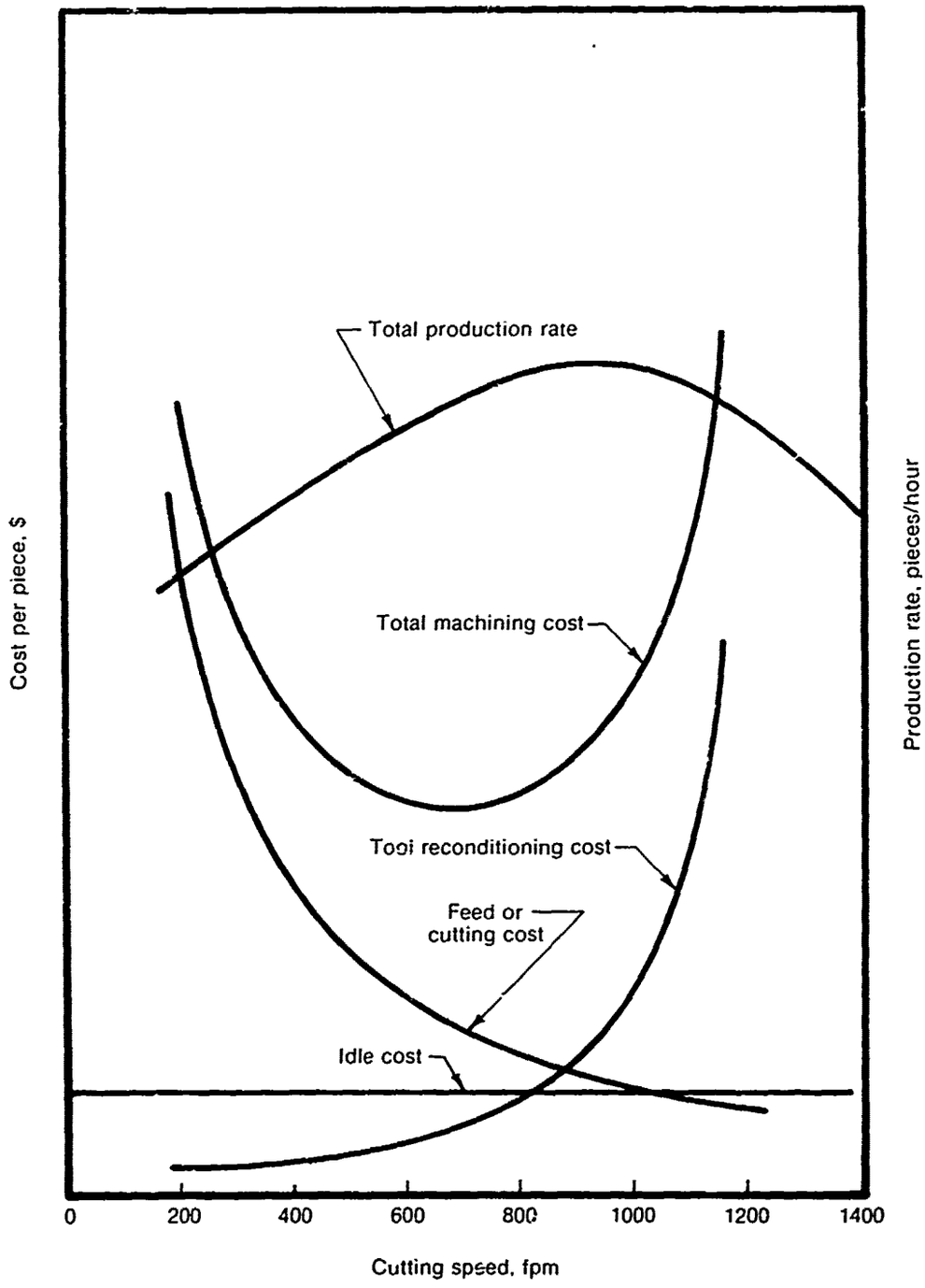


Figure 21–4 Machining cost and production rate versus cutting speed.

TABLE 21–3 Tool Life Data for Turning

MATERIAL	CONDITION AND MICROSTRUCTURE	HARDNESS Bhn	TOOL MATERIAL		TOOL GEOMETRY						CUTTING FLUID CODE *	DEPTH OF CUT in	FEED ipr	TOOL LIFE END POINT in	TOOL LIFE, min vs CUTTING SPEED, fpm			
			Trade Name	Industry Grade	BR°	SR°	SCEA°	ECEA°	Relief°	Nose Radius in								
Alloy Steels 8640	Quenched and tempered	400	—	T1 HSS	0	15	0	5	5	0.005	11 1:20	0.060	0.009	0.060	5	15	30	
	Tempered martensite														80	67	58	
8640	Annealed	170	78	C-7	0	6	0	6	6	0.040	00	0.100	0.010	0.015	15	30	45	60
	50%P-50%F														610	490	420	373
8640	Spheroidized	180	78	C-7	0	6	0	6	6	0.040	00	0.100	0.010	0.015	15	30	45	60
	Spheroidized carbides + ferrite														695	580	525	485
8640	Annealed	190	78	C-7	0	6	0	6	6	0.040	00	0.100	0.010	0.015	15	30	45	60
	75%P-25%F														590	450	380	335
8640	Annealed	250	78B	C-6	0	6	0	6	6	0.040	00	0.100	0.010	0.015	1	6	20	66
	Widmanstätten														910	600	440	300
8640	Annealed	250	78	C-7	0	6	0	6	6	0.040	00	0.100	0.010	0.015	15	30	45	60
	Widmanstätten														640	520	440	375
8640	Quenched and tempered	300	78	C-7	0	6	0	6	6	0.040	00	0.100	0.010	0.015	5	15	20	
	Tempered martensite														660	400	315	
8640	Quenched and tempered	400	78	C-7	0	6	0	6	6	0.040	00	0.100	0.010	0.015	5	15	20	
	Tempered martensite														480	365	318	
52100	Spheroidized	190	—	T1 HSS	0	15	0	5	5	0.005	11 1:20	0.060	0.009	0.060	15	30	35	
	Spheroidized carbides + ferrite														137	123	120	
52100	Spheroidized	190	78B	C-6	0	6	0	6	6	0.040	00	0.100	0.010	0.015	15	30	45	
	Spheroidized carbides + ferrite														430	340	300	

*Cutting Fluid Code
00 Dry
11 Soluble Oil

TABLE 21–4 Tool Life Data for Milling

FACE MILLING

MATERIAL	CONDITION AND MICROSTRUCTURE	HARDNESS Bhn	TOOL MATL. Trade Name	TOOL MATL. Industry Grade	UP OR DOWN MILLING	TOOL GEOMETRY AR°	RR°	CA°	FR°	Incl°	ECEA°	End Rel.° / Cor. Rel.°	CUTTING FLUID CODE *	DEPTH OF CUT in	WIDTH OF CUT in	FEED PER TOOTH in	TOOL LIFE END POINT in	TOOL LIFE/TOOTH inches work travel vs CUTTING SPEED, fpm			
Stainless steels Martensitic 410	Quenched & tempered	353	370	C-6	Up	0	−7	45	−5	5	5	8	00	0.100	2 0	0.010	0.016	15	45	60	90
	Tempered martensite											8						540	420	365	230
410	Quenched & tempered	45 R_c	—	T15 HSS	Up	0	0	45	0	0	5	8	11 1:20	0.060	2.0	0.005	0 060	15	30	50	
	Tempered martensite											8						100	79	68	

END MILL SLOTTING

MATERIAL	CONDITION AND MICROSTRUCTURE	HARDNESS Bhn	TOOL MATL. Trade Name	TOOL MATL. Industry Grade	CUTTER TYPE	DIA. in	NO. TEETH	FLUTE LENGTH in	UP OR DOWN MILLING	TOOL GEOMETRY Helix Angle°	RR°	Chamfer	ECEA°	End Rel.° / Periph. Rel.°	CUTTING FLUID CODE *	DEPTH OF CUT in	WIDTH OF CUT in	FEED PER TOOTH in	TOOL LIFE END POINT in	TOOL LIFE/CUTTER inches work travel vs CUTTING SPEED, fpm			
Alloy steel 4340	Annealed	213	—	M2 HSS	Solid HSS	0.750	4	2	—	30	10	45° x 0.060 in	1	3	11 1:20	0.250	0.750	0.002	0.012	50	120	240	
	Spheroidized carbides ferrite													7						190	153	125	

PERIPHERAL END MILLING

MATERIAL	CONDITION AND MICROSTRUCTURE	HARDNESS Bhn	TOOL MATL. Trade Name	TOOL MATL. Industry Grade	CUTTER TYPE	DIA. in	NO. TEETH	FLUTE LENGTH in	UP OR DOWN MILLING	TOOL GEOMETRY Helix Angle°	RR°	Chamfer	ECEA°	End Rel.° / Periph. Rel.°	CUTTING FLUID CODE *	DEPTH OF CUT in	WIDTH OF CUT in	FEED PER TOOTH in	TOOL LIFE END POINT in	TOOL LIFE/CUTTER inches work travel vs CUTTING SPEED, fpm			
High strength steel D6ac	Annealed	223	—	M2 HSS	Solid HSS	0.750	4	2	Down	30	10	45° x 0.060 in	1	3	11 1:20 Mist	0 250	0 750	0.004	0.012	75	130	260	
	60% P-40% F													7						290	240	190	

*Cutting Fluid Code
00 Dry
11 Soluble Oil

TABLE 21–5 Tool Life Data for Drilling, Reaming and Tapping

DRILLING

MATERIAL	CONDITION AND MICROSTRUCTURE	HARDNESS Bhn	DRILL MATL. Trade Name	DRILL MATL. Industry Grade	TYPE DRILL	DRILL SIZE Dia. in	DRILL SIZE Length in	DRILL SIZE Flute Length in	DRILL GEOMETRY Type Point	DRILL GEOMETRY Helix Angle°	DRILL GEOMETRY Point Angle°	DRILL GEOMETRY Lip Relief°	CUTTING FLUID CODE *	DEPTH OF HOLE in	FEED ipr	DRILL LIFE END POINT in	DRILL LIFE no. of holes vs CUTTING SPEED, fpm				
Alloy steel 4340	Quenched & tempered	341	—	M2 HSS	Twist	0.250	4.0	2.75	Standard	29	118	7	31	0.5 thru	0.002	0.015	25	50	75	100	
	Tempered martensite																98	84	76	70	
"	"	"	—	"	"	"	"	"	"	"	"	"	"	"	0.005	"	25	50	75	100	
	"																80	65	56	50	

REAMING

MATERIAL	CONDITION AND MICROSTRUCTURE	HARDNESS Bhn	REAMER DESCRIPTION TOOL MATL. Trade Name	REAMER DESCRIPTION TOOL MATL. Industry Grade	REAMER DESCRIPTION Dia. in	REAMER DESCRIPTION No. of Flutes	REAMER DESCRIPTION Style	TOOL GEOMETRY Helix & Hand	TOOL GEOMETRY Chamfer	TOOL GEOMETRY Rel.°	CUTTING FLUID CODE *	STOCK ALLOW. ON DIA. in	LENGTH OF HOLE in	FEED ipr	TOOL LIFE END POINT in	REAMER LIFE no of holes vs CUTTING SPEED, fpm				
High strength steel 250 Grade maraging steel	Annealed & maraged	50 R$_c$	—	M2 HSS	0.272	6	Chucking	0° RH	45° x 0.060 in	7	52	0.022	0.5 thru	0.005	0.006	20	35	170		
	Martensite															90	80	50		

TAPPING

MATERIAL	CONDITION AND MICROSTRUCTURE	HARDNESS Bhn	TAP MATERIAL	TAP SIZE	NO. OF FLUTES	TAP STYLE	PERCENT OF THREAD	CUTTING FLUID CODE *	DEPTH OF HOLE in	TAP LIFE END POINT in	TAP LIFE no of holes vs CUTTING SPEED, fpm				
High temperature alloy—iron base, wrought A-286	Solution treated & aged	320	M10 HSS	5/16-18NC	2	Plug spiral point	75	53	0.5 thru	Tap breakage	12	31	132		
	Austenitic										50	40	30		

*Cutting Fluid Code
31 Sulfurized mineral oil + fatty oil—light duty
52 Sulfo-chlorinated mineral oil + fatty oil—medium duty
53 Highly chlorinated mineral oil—heavy duty

TABLE 21–6 Generalized Machining Cost Equations for Use with English Units

Turning

$$C = M\left[\frac{D(L+e)}{3.82f_r\,v} + \frac{R}{r} + t_l + \frac{DLt_d}{3.82f_r\,vT}\right] + \frac{DL}{3.82f_r\,vT}\left[\frac{C_p}{(K_1+1)} + Gt_s + \frac{Gt_b}{k_2} + \frac{C_c}{k_3} + C_w + Gt_p\right]$$

Milling

$$C = M\left[\frac{D(L+e)}{3.82Zf_t\,v} + \frac{R}{r} + t_l + \frac{Lt_d}{ZT_t}\right] + \frac{L}{ZT_t}\left[\frac{C_p}{(K_1+1)} + Gt_s + \frac{Gt_b}{k_2} + \frac{ZC_c}{k_3} + C_w + Gt_p\right]$$

Drilling or Reaming

$$C = M\left[\frac{D(L+e)}{3.82f_r\,v} + \frac{R}{r} + t_l + \frac{Lt_d}{T_t}\right] + \frac{L}{T_t}\left[\frac{C_p}{(K_1+1)} + Gt_s + Gt_p\right]$$

Tapping

$$C = M\left[\frac{mD(L+e)}{1.91v} + \frac{R}{r} + t_l + \frac{Lt_d}{T_t}\right] + \frac{L}{T_t}\left[\frac{C_p}{(K_1+1)} + Gt_s + Gt_p\right]$$

Center Drilling or Chamfering

$$C = M\left[\frac{D(L+e)}{3.82f_r\,v} + \frac{R}{r} + t_l + \frac{u_c t_d}{T_h}\right] + \frac{u_c}{T_h}\left[\frac{C_p}{(K_1+1)} + Gt_s + Gt_p\right]$$

Handling and Setup

$$C = M\left[t_l + \frac{t_o}{N_t}\right]$$

$/Min	Feeding Time	Rapid Traverse Time	Load & Unload Time	Setup Time	Cutter Index Time	Dull Tool Replacement Time	Tool Depreciation Cost	Tool Resharpening Cost	Rebrazing or Blade Reset Cost	Insert or Blade Cost	Grinding Wheel Cost	Tool Presetting Cost

TABLE 21–7 Generalized Machining Cost Equations for Use with Metric Units

Turning

$$C = M\left[\frac{D(L+e)}{318f_r v} + \frac{R}{r} + t_l + \frac{DLt_d}{318f_r vT}\right] + \frac{DL}{318f_r vT}\left[\frac{C_p}{(K_1+1)} + Gt_s + \frac{Gt_b}{k_2} + \frac{C_c}{k_3} + C_w + Gt_p\right]$$

Milling

$$C = M\left[\frac{D(L+e)}{318Zf_t v} + \frac{R}{r} + t_l + \frac{Lt_d}{ZT_t}\right] + \frac{L}{ZT_t}\left[\frac{C_p}{(K_1+1)} + Gt_s + \frac{Gt_b}{k_2} + \frac{ZC_c}{k_3} + C_w + Gt_p\right]$$

Drilling or Reaming

$$C = M\left[\frac{D(L+e)}{318f_r v} + \frac{R}{r} + t_l + \frac{Lt_d}{T_t}\right] + \frac{L}{T_t}\left[\frac{C_p}{(K_1+1)} + Gt_s + Gt_p\right]$$

Tapping

$$C = M\left[\frac{D(L+e)}{159pv} + \frac{R}{r} + t_l + \frac{Lt_d}{T_t}\right] + \frac{L}{T_t}\left[\frac{C_p}{(K_1+1)} + Gt_s + Gt_p\right]$$

Center Drilling or Chamfering

$$C = M\left[\frac{D(L+e)}{318f_r v} + \frac{R}{r} + t_l + \frac{u_c t_d}{T_h}\right] + \frac{u_c}{T_h}\left[\frac{C_p}{(K_1+1)} + Gt_s + Gt_p\right]$$

Handling and Setup

$$C = M\left[t_l + \frac{t_o}{N_t}\right]$$

$\frac{\$}{\text{Min}}$	Feeding Time	Rapid Traverse Time	Load & Unload Time	Setup Time	Cutter Index Time	Dull Tool Replacement Time	Tool Depreciation Cost	Tool Resharpening Cost	Rebrazing or Blade Reset Cost	Insert or Blade Cost	Grinding Wheel Cost	Tool Presetting Cost

TABLE 21–8 Equations for Calculating Operating Time Per Piece and Production Rate When Using English Units

EQUATIONS FOR OPERATING TIME PER PIECE

Turning

$$t_m = \frac{D(L+e)}{3.82f_r v} + \frac{R}{r} + t_l + \frac{DLt_d}{3.82f_r vT}$$

Milling

$$t_m = \frac{D(L+e)}{3.82Zf_t v} + \frac{R}{r} + t_l + \frac{Lt_d}{ZT_t}$$

Drilling and Reaming

$$t_m = \frac{D(L+e)}{3.82f_r v} + \frac{R}{r} + t_l + \frac{Lt_d}{T_t}$$

Tapping

$$t_m = \frac{mD(L+e)}{1.91v} + \frac{R}{r} + t_l + \frac{Lt_d}{T_t}$$

Center Drilling or Chambering

$$t_m = \frac{D(L+e)}{3.82f_r v} + \frac{R}{r} + t_l + \frac{u_c t_d}{T_h}$$

EQUATION FOR PRODUCTION RATE

$$P = \frac{60}{\left(\Sigma t_m + t_L + \frac{t_o}{N_L}\right)}$$

TABLE 21–9 Equations for Calculating Operating Time Per Piece and Production Rate When Using Metric Units

EQUATIONS FOR OPERATING TIME PER PIECE

Turning

$$t_m = \frac{D(L+e)}{318f_r v} + \frac{R}{r} + t_l + \frac{DLt_d}{318f_r vT}$$

Milling

$$t_m = \frac{D(L+e)}{318Zf_t v} + \frac{R}{r} + t_l + \frac{Lt_d}{ZT_t}$$

Drilling and Reaming

$$t_m = \frac{D(L+e)}{318f_r v} + \frac{R}{r} + t_l + \frac{Lt_d}{T_t}$$

Tapping

$$t_m = \frac{D(L+e)}{159pv} + \frac{R}{r} + t_l + \frac{Lt_d}{T_t}$$

Center Drilling or Chamfering

$$t_m = \frac{D(L+e)}{318f_r v} + \frac{R}{r} + t_l + \frac{u_c t_d}{T_h}$$

EQUATION FOR PRODUCTION RATE

$$P = \frac{60}{\left(\Sigma t_m + t_L + \frac{t_o}{N_L}\right)}$$

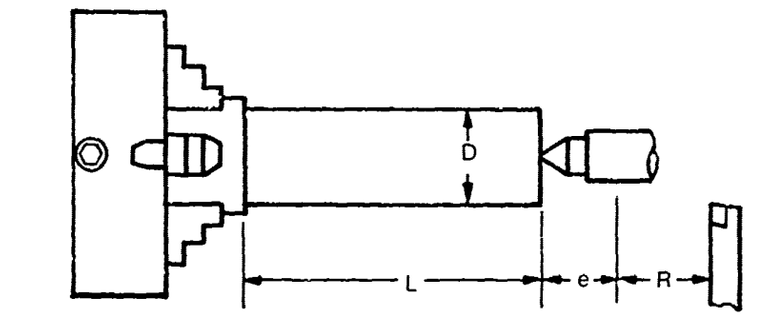
TABLE 21–10 Cost and Production Rate Equation Variables
(Definitions and applications for variables in English units)

VARIABLE	DEFINITION	APPLIES TO OPERATION				
		Turn	Mill	Drill and Ream	Tap	Center Drill
C	Cost for machining one workpiece; $/workpiece	✓	✓	✓	✓	✓
C_c	Cost of each insert or inserted blade; $/blade	✓	✓	No	No	No
C_p	Purchase cost of tool or cutter; $/cutter	✓	✓	✓	✓	✓
C_w	Cost of grinding wheel for resharpening tool or cutter; $/cutter	✓	✓	No	No	No
d	Depth of cut, in	✓	✓	No	No	No
D	Dia. of work in turning, of tool in milling, drilling, reaming, tapping; in	✓	✓	✓	✓	✓
e	Extra travel at feedrate (f_r or f_t) including approach, overtravel, and all positioning moves; in	✓	✓	✓	✓	✓
f_r	Feed per revolution; in	✓	No	✓	No	✓
f_t	Feed per tooth; in	No	✓	No	No	No
G	Labor + overhead in tool reconditioning department; $/min	✓	✓	✓	✓	✓
k_1	No. of times lathe tool, or milling cutter, or drill, or reamer or tap is resharpened before being discarded	✓	✓	✓	✓	✓
k_2	No. of times lathe tool or milling cutter is resharpened before inserts or blades are rebrazed or reset	✓	✓	No	No	No
k_3	No. of times blades (or inserts) are resharpened (or indexed) before blades (or inserts) are discarded	✓	✓	No	No	No
L	Length of workpiece in turning and milling or sum of length of all holes of same diameter in drilling, reaming, tapping; in	✓	✓	✓	✓	✓
m	No. of threads per inch	No	No	No	✓	No
M	Labor + overhead cost on lathe, milling machine or drilling machine; $/min	✓	✓	✓	✓	✓
n	Tool life exponent in Taylor's Equation	✓	✓	✓	✓	No
N_L	No. of workpieces in lot	✓	✓	✓	✓	✓
N_s	No. of pieces between sharpenings	✓	✓	✓	✓	✓
P	Production rate per hour; workpieces/hour	✓	✓	✓	✓	✓
r	Rapid traverse rate; in/min	✓	✓	✓	✓	✓
R	Total rapid traverse distance for a tool or cutter on one part; in	✓	✓	✓	✓	✓
S	Reference cutting speed for a tool life of T = 1 min; fpm	✓	No	No	No	No
S_t	Reference cutting speed for a tool life of T_t = 1 inch; fpm	No	✓	✓	✓	No
t_b	Time to rebraze lathe tool or cutter teeth or reset blades; min	✓	✓	No	No	No
t_d	Time to replace dull cutter in tool changer storage unit; min	✓	✓	✓	✓	✓
t_i	Time to index from one type cutter to another between operations (automatic or manual); min	✓	✓	✓	✓	✓
t_L	Time to load and unload workpiece; min	✓	✓	✓	✓	✓
t_m	Time (average) to complete one operation; min	✓	✓	✓	✓	✓
t_o	Time to setup machine tool for operation; min	✓	✓	✓	✓	✓
t_p	Time to preset tools away from machine (in toolroom); min	✓	✓	✓	✓	✓
t_s	Time to resharpen lathe tool, milling cutter, drill, reamer or tap; min/tool	✓	✓	✓	✓	✓
T	Tool life measured in minutes to dull a lathe tool; min	✓	No	No	No	No
T_h	No. of holes per resharpening	No	No	No	No	✓
T_t	Tool life measured in inches travel of work or tool to dull a drill, reamer, tap or one milling cutter tooth; in	No	✓	✓	✓	No
u_c	No. of holes center drilled or chamfered in workpiece	No	No	No	No	✓
v	Cutting speed; fpm	✓	✓	✓	✓	✓
w	Width of cut; in	No	✓	No	No	No
Z	No. of teeth in milling cutter or no. of flutes in a tap	No	✓	No	✓	No

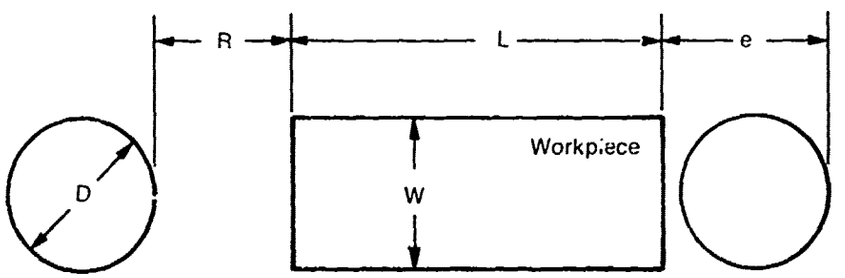
TABLE 21-11 Cost and Production Rate Equation Variables

(Definitions and applications for variables in metric units)

VARIABLE	DEFINITION	APPLIES TO OPERATION				
		Turn	Mill	Drill and Ream	Tap	Center Drill
C	Cost for machining one workpiece; $/workpiece	✓	✓	✓	✓	✓
C	Cost of each insert or inserted blade; $/blade	✓	✓	No	No	No
C_p	Purchase cost of tool or cutter; $/cutter	✓	✓	✓	✓	✓
C_w	Cost of grinding wheel for resharpening tool or cutter; $/cutter	✓	✓	No	No	No
d	Depth of cut; mm	✓	✓	No	No	No
D	Dia. of work in turning, of tool in milling, drilling, reaming, tapping; mm	✓	✓	✓	✓	✓
e	Extra travel at feedrate (f_r or f_t) including approach, overtravel, and all positioning moves; mm	✓	✓	✓	✓	✓
f_r	Feed per revolution; mm	✓	No	✓	No	✓
f_t	Feed per tooth; mm	No	✓	No	No	No
G	Labor + overhead in tool reconditioning department; $/min	✓	✓	✓	✓	✓
k_1	No. of times lathe tool, or milling cutter, or drill, or reamer or tap is resharpened before being discarded	✓	✓	✓	✓	✓
k_2	No. of times lathe tool or milling cutter is resharpened before inserts or blades are rebrazed or reset	✓	✓	No	No	No
k_3	No. of times blades (or inserts) are resharpened (or indexed) before blades (or inserts) are discarded	✓	✓	No	No	No
L	Length of workpiece in turning and milling or sum of length of all holes of same diameter in drilling, reaming, tapping; mm	✓	✓	✓	✓	✓
M	Labor + overhead cost on lathe, milling machine or drilling machine; $/min	✓	✓	✓	✓	✓
n	Tool life exponent in Taylor's Equation	✓	✓	✓	✓	No
N_L	No. of workpieces in lot	✓	✓	✓	✓	✓
N_s	No. of pieces between sharpenings	✓	✓	✓	✓	✓
p	Pitch of thread, mm	No	No	No	✓	No
P	Production rate per hour; workpieces/hour	✓	✓	✓	✓	✓
r	Rapid traverse rate; mm/min	✓	✓	✓	✓	✓
R	Total rapid traverse distance for a tool or cutter on one part; mm	✓	✓	✓	✓	✓
S	Reference cutting speed for a tool life of T = 1 min; m/min	✓	No	No	No	No
S_t	Reference cutting speed for a tool life of T_t = 1 mm; m/min	No	✓	✓	✓	No
t_b	Time to rebraze lathe tool or cutter teeth or reset blades; min	✓	✓	No	No	No
t_d	Time to replace dull cutter in tool changer storage unit; min	✓	✓	✓	✓	✓
t_i	Time to index from one type cutter to another between operations (automatic or manual); min	✓	✓	✓	✓	✓
t_l	Time to load and unload workpiece; min	✓	✓	✓	✓	✓
t_m	Time (average) to complete one operation; min	✓	✓	✓	✓	✓
t_o	Time to setup machine tool for operation; min	✓	✓	✓	✓	✓
t_p	Time to preset tools away from machine (in toolroom); min	✓	✓	✓	✓	✓
t_s	Time to resharpen lathe tool, milling cutter, drill, reamer or tap; min/tool	✓	✓	✓	✓	✓
T	Tool life measured in minutes to dull a lathe tool; min	✓	No	No	No	No
T_h	No. of holes per resharpening	No	No	No	No	✓
T_t	Tool life measured in mm travel of work or tool to dull a drill, reamer, tap or one milling cutter tooth; mm	No	✓	✓	✓	No
u_c	No. of holes center drilled or chamfered in workpiece	No	No	No	No	✓
v	Cutting speed; m/min	✓	✓	✓	✓	✓
w	Width of cut; mm	No	✓	No	No	No
Z	No. of teeth in milling cutter or no. of flutes in a tap	No	✓	No	✓	No



Turning



Milling

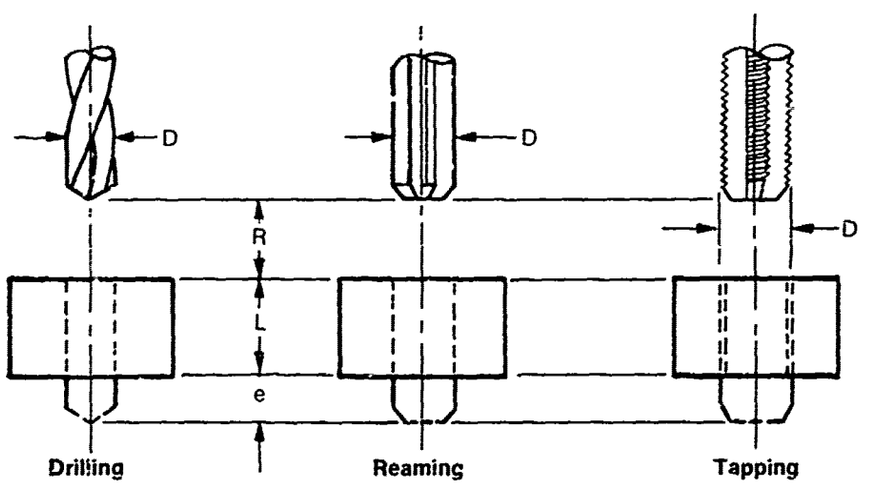


Figure 21–5 Setups for various machining operations.

TABLE 21–12 Derivation of Terms in Cost Equations for Turning and Milling

TERMS	TURNING	MILLING
rpm to Cut speed	$v = \frac{\pi D \times rpm}{12}$; $rpm = \frac{3.82\,v}{D}$	$rpm = \frac{3.82\,v}{D}$
Feed rate, in/min	$\frac{in}{rev} \times \frac{rev}{min} = f_r \times \frac{3.82\,v}{D}$	$\frac{in}{tooth} \times \text{no. teeth} \times \frac{rev}{min} = f_t \times Z \times \frac{3.82\,v}{D}$
N_s = No. pieces between sharpenings	$\frac{\text{Tool life, min}}{\text{Feed time, min}} = \frac{3.82\,f_r\,v\,T}{DL}$	$\frac{\text{Tool life (Total length cut, in)}}{\text{Length each piece, in}} = \frac{Z\,T_t}{L}$
Feed time = $\frac{\text{Distance in feed}}{\text{in/min}}$	$\frac{L+e}{\frac{3.82\,f_r\,v}{D}} = \frac{D(L+e)}{3.82\,f_r\,v}$	$\frac{(e+L)\,D}{3.82\,Z\,f_t\,v}$
Rapid traverse time	$\frac{R}{r}$	$\frac{R}{r}$
Setup time = $\frac{\text{Time to set up}}{\text{No. pieces in lot}}$	$\frac{t_o}{N_L}$	$\frac{t_o}{N_L}$
Tool change time = $\frac{\text{Time to change tool}}{N_s = \text{No. pieces between sharpenings}}$	$\frac{DL\,t_d}{3.82\,f_r\,v\,T}$	$\frac{L\,t_d}{Z\,T_t}$
Tool deprec. cost $\frac{1}{N_s} \times \frac{\text{Purchased cost of cutter}}{\text{No. times cutter is resharpened before discarding}}$	$\frac{i}{N_s} \times \frac{C_p}{(k_1+1)}$	$\frac{1}{N_s} \times \frac{C_p}{k_1+1}$
Tool resharp. cost = $\frac{1}{N_s} \times G \times$ Time to resharpen cutter	$\frac{1}{N_s} \times G\,t_s$	$\frac{1}{N_s} \times G\,t_s$
Rebraze (or blade reset) cost = $\frac{1}{N_s} \times \frac{\text{Time to rebraze}}{\text{No. times tool is resharpened before blades are rebrazed}}$	$\frac{1}{N_s} \times G\,\frac{t_b}{k_2}$	$\frac{1}{N_s} \times G\,\frac{t_b}{k_2}$
Insert or blade cost = $\frac{1}{N_s} \times \frac{\text{Cost of each insert or blade}}{\text{No. times blades are resharpened before blades are discarded}}$	$\frac{1}{N_s} \times \frac{C_c}{k_3}$	$\frac{1}{N_s} \times \frac{Z\,C_c}{k_3}$
Grinding wheel cost = $\frac{1}{N_s} \times$ Cost of grinding wheel for resharpening tool or cutter	$\frac{1}{N_s} \times C_w$	$\frac{1}{N_s} \times C_w$

TABLE 21–13 Time Study and Cost Data for Turning 4340 Steel Shaft

VARIABLE	DEFINITION	BRAZED CARBIDE TOOL	THROWAWAY CARBIDE TOOL	SOLID HSS TOOL
R	Total rapid traverse distance for a tool on one part, in	27.2	27.2	27.2
C_c	Cost of each carbide tip or insert, $	5.00	3.15	—
C_p	Purchase cost of tool, $	6.70	28.30	18 30
C_w	Cost of grinding wheel for resharpening tool, $	0.07	—	0 02
d	Depth of cut, in	0.1	0.1	0.1
D	Diameter of work in turning, in	3.5	3 5	3 5
f_r	Feed per revolution, in	*	*	*
G	Labor and overhead cost on tool grinder, $/min	0.40	—	0 40
k_1	No of times lathe tool is resharpened before discarding (or no. times insert is indexed before throwaway holder is discarded	12	2000	36
k_2	No. of times lathe tool is resharpened before rebrazing or resetting	6	—	—
k_3	No. of times insert is resharpened (or indexed) before insert is discarded	12	8	—
L	Length of workpiece in turning, in	19	19	19
M	Labor and overhead cost on lathe, $/min	0.15	0.15	0.15
N_L	No. of pieces in lot	20	20	20
r	Rapid traverse rate, in/min	100	100	100
t_b	Time to rebraze lathe tool, min	10	—	—
t_d	Time to change and reset tool or time to index throwaway insert, min	5	4	5
t_l	Time to load and unload workpiece, min	2.3	2.3	2.3
t_o	Time to set up lathe for operation, min	21	21	21
t_s	Time to resharpen tool, min	15	—	10
T	Tool life, total time to dull tool, min	*	*	*
v	Cutting speed, fpm	*	*	*
e	Extra travel of tool in feed (includes approach and overtravel in feed)	0.5	0.5	0.5

*These values are taken from Tool Life Data, table 21–14.

TABLE 21–14 Tool Life Data for Turning 4340 Steel

MATERIAL	CONDITION AND MICROSTRUCTURE	HARDNESS Bhn	TOOL MATERIAL		TOOL GEOMETRY						CUTTING FLUID CODE *	DEPTH OF CUT in	FEED ipr	TOOL LIFE END POINT in	TOOL LIFE, min vs CUTTING SPEED, fpm			
			Trade Name	Industry Grade	BR°	SR°	SCEA°	ECEA°	Relief°	Nose radius in					① 15	② 30	③ 45	④ 60
4340	Quenched and tempered	300	78	C-7	0	6	0	6	6	0.040	00	0.100	0.010	0.015	470	400	360	325
	Tempered martensite																	
4340	Quenched and tempered	300	—	T1 HSS	0	15	0	5	5	0.005	11 1:20	0.060	0.010	0.060	⑤ 15	⑥ 30	⑦ 45	⑧ 60
	Tempered martensite														77	63	54	45

*Cutting Fluid Code
00 Dry
11 Soluble Oil

COST AND PRODUCTION RATE FOR TURNING

BRAZED CARBIDE TOOLS

DATA SET NO.	WORK MATERIAL	HARDNESS	TOOL MATL	CUT SPD F/M	FEED IN/REV	TOOL LIFE MIN	FEED COST $	RAPD TRAV $	LOAD UNLD $	SET UP $	TOOL CHNG $	TOOL DEPR $	TOOL SHPN $	RE BRAZ $	TIP COST $	GRIND WHEEL $	TOTAL COST $/PC	PROD RATE PC/HR
1	AISI 4340	300	C-7	470	0.0100	15	1.50	0.11	0.92	0.42	0.49	0.13	1.48	0.16	0.10	0.02	5.33	7.0
2	AISI 4340	300	C-7	400	0.0100	30	1.76	0.11	0.92	0.42	0.29	0.07	0.87	0.10	0.06	0.01	4.61	6.9
3	AISI 4340	300	C-7	360	0.0100	45	1.95	0.11	0.92	0.42	0.21	0.06	0.64	0.07	0.04	0.01	4.44	6.6
4	AISI 4340	300	C-7	325	0.0100	60	2.17	0.11	0.92	0.42	0.18	0.05	0.54	0.06	0.04	0.01	4.48	6.3

COST AND PRODUCTION RATE FOR TURNING

THROWAWAY CARBIDE TOOLS

DATA SET NO.	WORK MATERIAL	HARDNESS	TOOL MATL	CUT SPD F/M	FEED IN/REV	TOOL LIFE MIN	FEED COST $	RAPD TRAV $	LOAD UNLD $	SET UP $	INDX INST $	HLDR DEPR $	INSERT COST $	TOTAL COST $/PC	PROD RATE PC/HR
1	AISI 4340	300	C-7	470	0.0100	15	1.50	0.11	0.92	0.42	0.04	0.00	0.10	3.09	8.0
2	AISI 4340	300	C-7	400	0.0100	30	1.76	0.11	0.92	0.42	0.02	0.00	0.06	3.29	7.4
3	AISI 4340	300	C-7	360	0.0100	45	1.95	0.11	0.92	0.42	0.02	0.00	0.04	3.46	7.0
4	AISI 4340	300	C-7	325	0.0100	60	2.17	0.11	0.92	0.42	0.01	0.00	0.04	3.66	6.6

COST AND PRODUCTION RATE FOR TURNING

SOLID HIGH SPEED STEEL TOOLS

DATA SET NO.	WORK MATERIAL	HARDNESS	TOOL MATL	CUT SPD F/M	FEED IN/REV	TOOL LIFE MIN	FEED COST $	RAPD TRAV $	LOAD UNLD $	SET UP $	TOOL CHNG $	TOOL DEPR $	TOOL SHPN $	GRIND WHEEL $	TOTAL COST $/PC	PROD RATE PC/HR
5	AISI 4340	300	T-1	77	0.0100	15	9.14	0.11	0.92	0.42	3.01	0.75	6.03	0.03	20.41	1.8
6	AISI 4340	300	T-1	63	0.0100	30	11.17	0.11	0.92	0.42	1.84	0.46	3.68	0.02	18.62	1.7
7	AISI 4340	300	T-1	54	0.0100	45	13.03	0.11	0.92	0.42	1.43	0.35	2.87	0.01	19.15	1.5
8	AISI 4340	300	T-1	45	0.0100	60	15.64	0.11	0.92	0.42	1.29	0.32	2.58	0.01	21.29	1.3

Figure 21–6 Printout of cost and production rate results for turning 4340 steel with three tool materials.

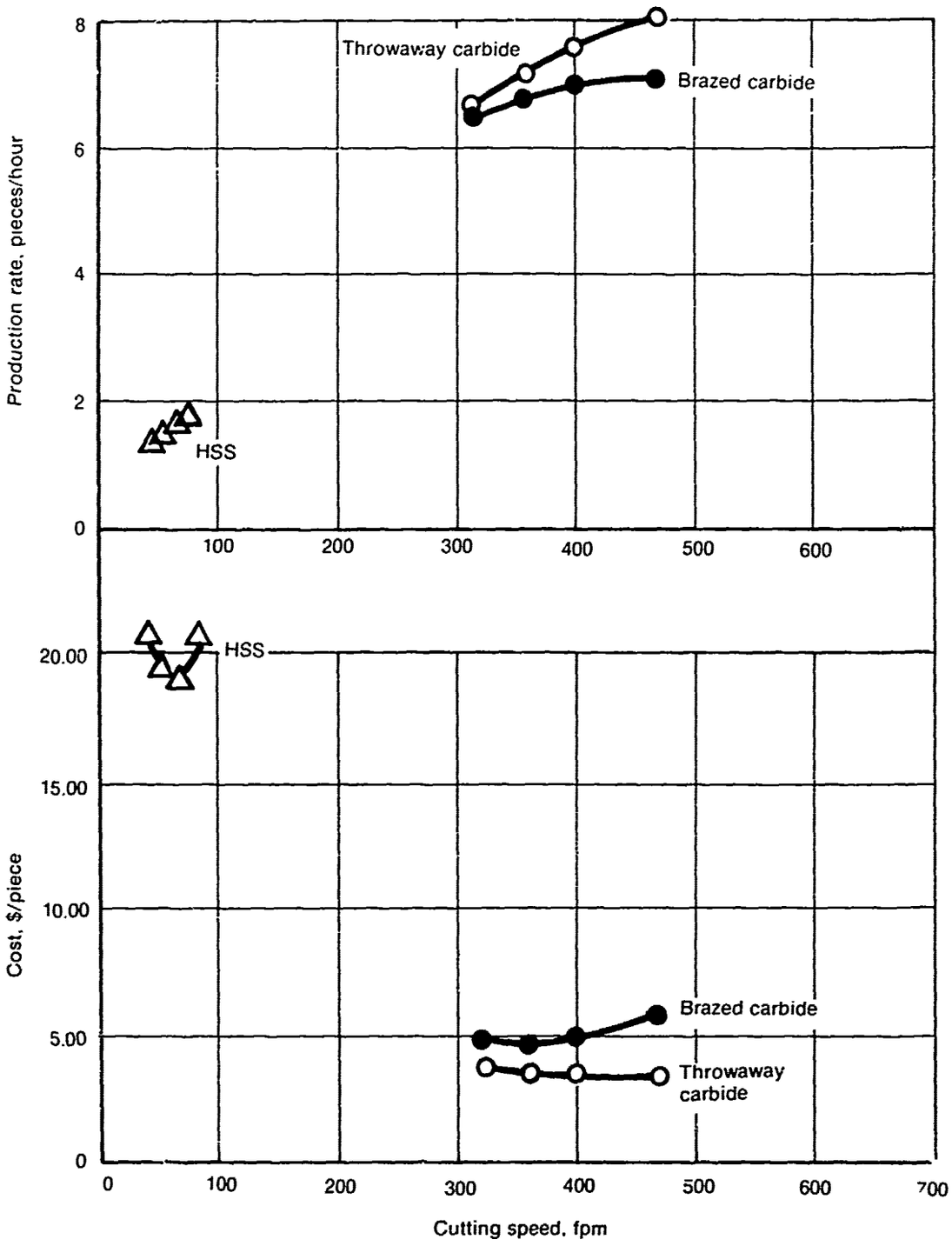


Figure 21-7 Cutting speed versus cost and production rate for turning 4340 steel (quenched and tempered, 300 Bhn) with three tool materials.

TABLE 21–15 Manual Cost Calculations for Turning 4340 Steel Shaft with Brazed Carbide Tool

Operation	Turn, shaft, 3.5-inch diameter by 19 inches long
Material:	4340 Steel, Q&T, 300 Bhn
References:	Table 21-13, Brazed carbide tools Table 21-14, Data set 1 Figure 21-6, Brazed carbide tools, data set 1

Feed cost $= M \times \frac{DL}{3.82\, f_r\, v} = \frac{0.40 \times 3.5 \times 19}{3.82 \times 0.010 \times 470} = \$1.48$

Rapid traverse cost $= M \times \frac{2a + L}{r} = 0.40 \times \frac{2 \times 4 + 19}{100} = \$0.11$

Load & unload cost $= M \times t_L = 0.40 \times 2.3 = \$0.92$

Setup cost $= M \times \frac{t_2}{N_L} = 0.40 \times \frac{21}{20} = \$0.43$

Tool change cost $= M \times \frac{DL\, t_c}{3.82\, f_r\, v\, T} = \frac{0.40 \times 3.5 \times 19 \times 5}{3.82 \times 0.010 \times 470 \times 15} = \$0.49$

Tool depreciation cost $= \frac{1}{N_s} \times \frac{C_p}{k_1 + 1} = \frac{DL}{3.82\, f_r\, vt} \times \frac{C_p}{k_1 + 1}$

$= \frac{3.5 \times 19}{3.82 \times 0.010 \times 470 \times 15} \times \frac{6.70}{12 + 1} = \frac{1}{4.04} \times \frac{6.70}{13} = \$0.13$

Tool resharpening cost $= \frac{1}{N_s} \times 0.40 \times t_s = \frac{1}{4.04} \times 0.40 \times 15 = \$1.48$

TABLE 21-16 Time Study and Cost Data for Face Milling, 2 Inches Wide by 8 Inches Long
(Material: 4340 steel, quenched and tempered, 341 Bhn)

VARIABLE	DEFINITION	INSERTED TOOTH CARBIDE TIP	THROWAWAY INSERT	SOLID HSS CUTTER
a	Approach of cutter to work, in	9 0	9.0	9 0
C_c	Cost of each inserted tooth, throwaway insert, or carbide tip, $	2 50	2.35	—
C_p	Purchase cost of cutter, $	137 00	248.00	310.00
C_w	Cost of grinding wheel for resharpening cutter, $/cutter	0.30	—	0 35
d	Depth of cut, in	*	*	*
D	Diameter of milling cutter, in	4.0	4.0	4.0
e	Overtravel of milling cutter past workpiece, in.	5.0	5.0	5.0
f_t	Feed per tooth, in	*	*	*
G	Labor and overhead cost on cutter grinder, $/min	0 40	—	0.40
k_1	No of times cutter is resharpened before being discarded	9000	9000	20
k_2	No of times cutter is resharpened before inserts (or blades) are reset (or rebrazed)	4	—	—
k_3	No of times blades (or inserts) are resharpened (or indexed) before blades (or inserts) are discarded	12	8	—
L	Length of workpiece, in	8.0	8 0	8.0
M	Labor and overhead cost on milling machine, $/min	0.40	0 40	0 40
N	No. of workpieces in lot	100	100	100
r	Rapid traverse rate, in/min	150	150	150
t_b	Time to reset blades or to rebraze cutter teeth, min	30	—	—
t_c	Time to change cutter or index all inserts in cutter, min	10.0	6.0	10.0
t_l	Time to load and unload workpiece, min	3	3	3
t_o	Time to set up milling machine for operation, min	60	60	60
t_s	Time to resharpen cutter, min/cutter	80	—	80
T_t	Tool life measured in inches travel of work to dull one cutter tooth, in	*	*	*
v	Cutting speed, fpm	*	*	*
w	Width of cut, in	2.0	2.0	2.0
Z	No. of teeth in milling cutter	6	6	14

*These values are taken from Tool Life Data, table 21-17

TABLE 21–17 Tool Life Data for Face Milling 4340 Steel

MATERIAL	CONDITION AND MICROSTRUCTURE	HARDNESS Bhn	TOOL MATL. Trade Name	TOOL MATL. Industry Grade	UP OR DOWN MILLING	TOOL GEOMETRY AR°	RR°	CA°	TR°	Incl°	ECEA°	End Rel.° / Cor. Rel.°	CUTTING FLUID CODE *	DEPTH OF CUT in	WIDTH OF CUT in	FEED PER TOOTH in	TOOL LIFE END POINT in	TOOL LIFE/TOOTH inches work travel vs CUTTING SPEED, fpm			
4340	Quenched & tempered	341	—	T15 HSS	Up	0	0	30	0	0	5	6	11 1:20	0.100	2.0	0.010	0.060	① 17	② 22	③ 32	
	Tempered martensite											6						93	76	62	
4340	Quenched & tempered	341	370	C-6	Up	0	−7	45	−5	5	5	6	00	0.100	2.0	0.005	0.016	④ 20	⑤ 50	⑥ 80	
	Tempered martensite											6						680	550	340	

*Cutting Fluid Code
00 Dry
11 Soluble Oil

21 ECONOMICS IN MACHINING AND GRINDING

COST AND PRODUCTION RATE FOR MILLING

INSERTED TOOTH - CARBIDE TIP

DATA SET NO.	WORK MATERIAL	HARD NESS	TOOL MATL	CUT SPD F/M	FEED/ TOOTH IN	TOOL LIFE IN/TH	FEED COST $	RAPD TRAV $	LOAD UNLD $	SET UP $	CUTR CHNG $	BODY DEPR $	CUTR SHPN $	BLAD RSET $	BLAD COST $	GRND WHL. $	TOTAL COST $/PC.	PROD RATE PC/HR
4	AISI 4340	341	C-6	680	0.005	20.0	0.27	0.08	1.20	0.24	0.27	0.00	2.13	0.20	0.08	0.02	4.49	11.7
5	AISI 4340	341	C-6	550	0.005	50.0	0.33	0.08	1.20	0.24	0.11	0.00	0.85	0.08	0.03	0.01	2.93	12.2
6	AISI 4340	341	C-6	340	0.005	80.0	0.53	0.08	1.20	0.24	0.07	0.00	0.53	0.05	0.02	0.00	2.73	11.3

COST AND PRODUCTION RATE FOR MILLING

THROWAWAY INSERT

DATA SET NO.	WORK MATERIAL	HARD NESS	TOOL MATL	CUT SPD F/M	FEED/ TOOTH IN	TOOL LIFE IN/TH	FEED COST $	RAPD TRAV $	LOAD UNLD $	SET UP $	INDX INST $	BODY DEPR $	INSERT COST $	TOTAL COST $/PC.	PROD RATE PC/HR
4	AISI 4340	341	C-6	680	0.005	20.0	0.27	0.08	1.20	0.24	0.16	0.00	0.12	2.07	12.3
5	AISI 4340	341	C-6	550	0.005	50.0	0.33	0.08	1.20	0.24	0.06	0.00	0.05	1.96	12.5
6	AISI 4340	341	C-6	340	0.005	80.0	0.53	0.08	1.20	0.24	0.04	0.00	0.03	2.13	11.4

COST AND PRODUCTION RATE FOR MILLING

SOLID HIGH SPEED STEEL CUTTER

DATA SET NO.	WORK MATERIAL	HARD NESS	TOOL MATL	CUT SPD F/M	FEED/ TOOTH IN	TOOL LIFE IN/TH	FEED COST $	RAPD TRAV $	LOAD UNLD $	SET UP $	CUTR CHNG $	CUTR DEPR $	CUTR SHPN $	GRND WHL. $	TOTAL COST $/PC.	PROD RATE PC/HR
1	AISI 4340	341	T15	93	0.010	17.0	0.42	0.08	1.20	0.24	0.13	0.50	1.08	0.01	3.66	11.6
2	AISI 4340	341	T15	76	0.010	22.0	0.51	0.08	1.20	0.24	0.10	0.38	0.83	0.01	3.36	11.2
3	AISI 4340	341	T15	62	0.010	32.0	0.63	0.08	1.20	0.24	0.07	0.26	0.57	0.01	3.06	10.8

Figure 21–8 Printout of cost and production rate results for face milling 4340 steel with three cutter materials.

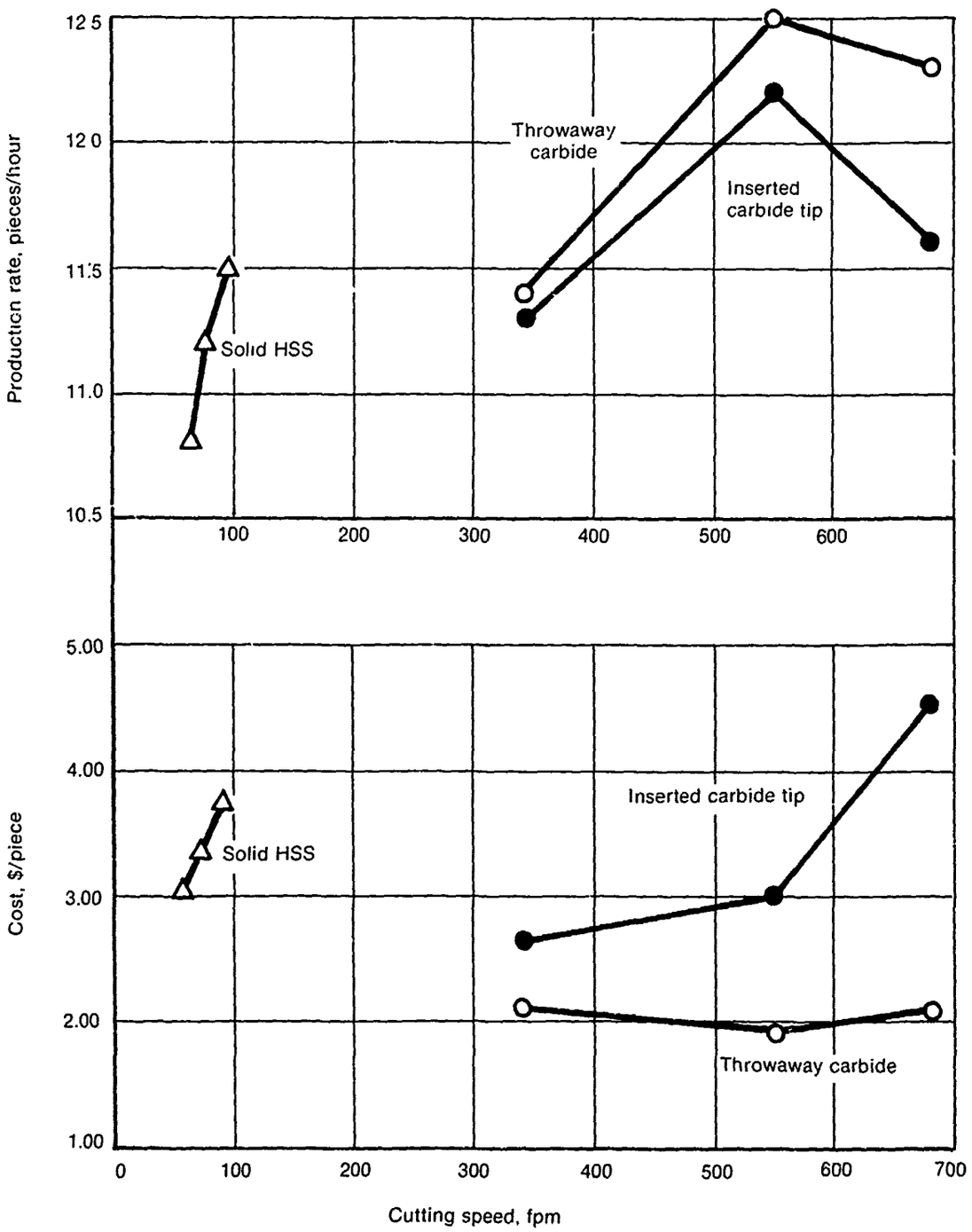


Figure 21–9 Cutting speed versus cost and production rate for face milling 4340 steel (quenched and tempered, 341 Bhn) with three tool materials.

TABLE 21–18 Time Study and Cost Data for Drilling Five Holes, 0.25-Inch Diameter by 0.5-Inch Deep
(Material: 4340 steel, annealed, 212 Bhn)

VARIABLE	DEFINITION	DATA
a	Approach of drill to work, in	3 0
C_p	Purchase cost of drill, $/drill	0.92
D	Diameter of drill, in	0.25
f_r	Feed per revolution, in	*
G	Labor and overhead cost on tool grinder, $/min	0.40
k_1	No. of times drill is resharpened before being discarded	12
L	Sum of lengths of all holes of same diameter, in	2.5
M	Labor and overhead cost on drilling machine, $/min	0.40
N_L	No. of workpieces in lot	70
r	Rapid traverse rate, in/min	100
t_c	Time to change drill, min	0.5
t_L	Time to load and unload workpiece, min	1.0
t_o	Time to set up drill for operation, min	25
t_s	Time to resharpen drill, min/drill	5
T_l	Tool life in inches travel of drill to dull drill, in	†
u	No of holes of same diameter in workpiece	5
v	Cutting speed, fpm	*
e	Extra travel in drilling, in	2.5

*These values are taken from Tool Life Data, table 21–19.
†Drill life data given in table 21–19 are in number of holes to dull drill, and equation requires these data in inches. Therefore, to obtain T_l, the number of holes is multiplied by the hole length (0 5 inch)

TABLE 21–19 Tool Life Data for Drilling Holes in 4340 Steel

MATERIAL	CONDITION AND MICROSTRUCTURE	HARDNESS Bhn	DRILL MATL. Trade Name	DRILL MATL. Industry Grade	TYPE DRILL	DRILL SIZE Dia. in	DRILL SIZE Length in	DRILL SIZE Flute Length in	DRILL GEOMETRY Type Point	DRILL GEOMETRY Helix Angle°	DRILL GEOMETRY Point Angle°	DRILL GEOMETRY Lip Relief°	CUTTING FLUID CODE *	LENGTH OF HOLE in	FEED ipr	DRILL LIFE END POINT in	DRILL LIFE no. of holes vs CUTTING SPEED, fpm				
4340	Annealed	212	—	M1 HSS	Twist	0.250	2.5	1.375	Standard	29	118	7	11 1·20	0 5 thru	0.002	0.015	① 30	② 50	③ 100	④ 220	
	Spheroidized carbides + ferrite																174	158	142	125	
"	"	"	—	"	"	"	"	"	"	"	"	"	"	"	0.005	"	⑤ 10	⑥ 100	⑦ 200	⑧ 280	
	"																140	97	82	75	

*Cutting Fluid Code
11 Soluble Oil

COST AND PRODUCTION RATE FOR DRILLING

DATA SET NO.	WORK MATERIAL	HARDNESS	TOOL MATL	CUT SPD F/M	FEED IN/REV	DRILL LIFE IN	FEED COST $	RAPD TRAV $	LOAD UNLD $	SET UP $	DRLL CHNG $	DRLL DEPR $	DRLL SHPN $	TOTAL COST $/PC	PROD RATE PC/HR
1	AISI 4340	212	M-1	174	0.0020	15.0	0.38	0.04	0.40	0.14	0.03	0.01	0.33	1.34	24.1
2	AISI 4340	212	M-1	158	0.0020	25.0	0.41	0.04	0.40	0.14	0.02	0.01	0.20	1.23	23.5
3	AISI 4340	212	M-1	142	0.0020	50.0	0.46	0.04	0.40	0.14	0.01	0.00	0.10	1.16	22.7
4	AISI 4340	212	M-1	125	0.0020	110.0	0.52	0.04	0.40	0.14	0.00	0.00	0.05	1.16	21.5
5	AISI 4340	212	M-1	140	0.0050	5.0	0.19	0.04	0.40	0.14	0.10	0.04	1.00	1.91	27.5
6	AISI 4340	212	M-1	97	0.0050	50.0	0.27	0.04	0.40	0.14	0.01	0.00	0.10	0.97	27.7
7	AISI 4340	212	M-1	82	0.0050	100.0	0.32	0.04	0.40	0.14	0.00	0.00	0.05	0.96	26.3
8	AISI 4340	212	M-1	75	0.0050	140.0	0.35	0.04	0.40	0.14	0.00	0.00	0.04	0.98	25.5

Figure 21–10 Printout of cost and production rate results for drilling 4340 steel with M-1 high speed steel tool.

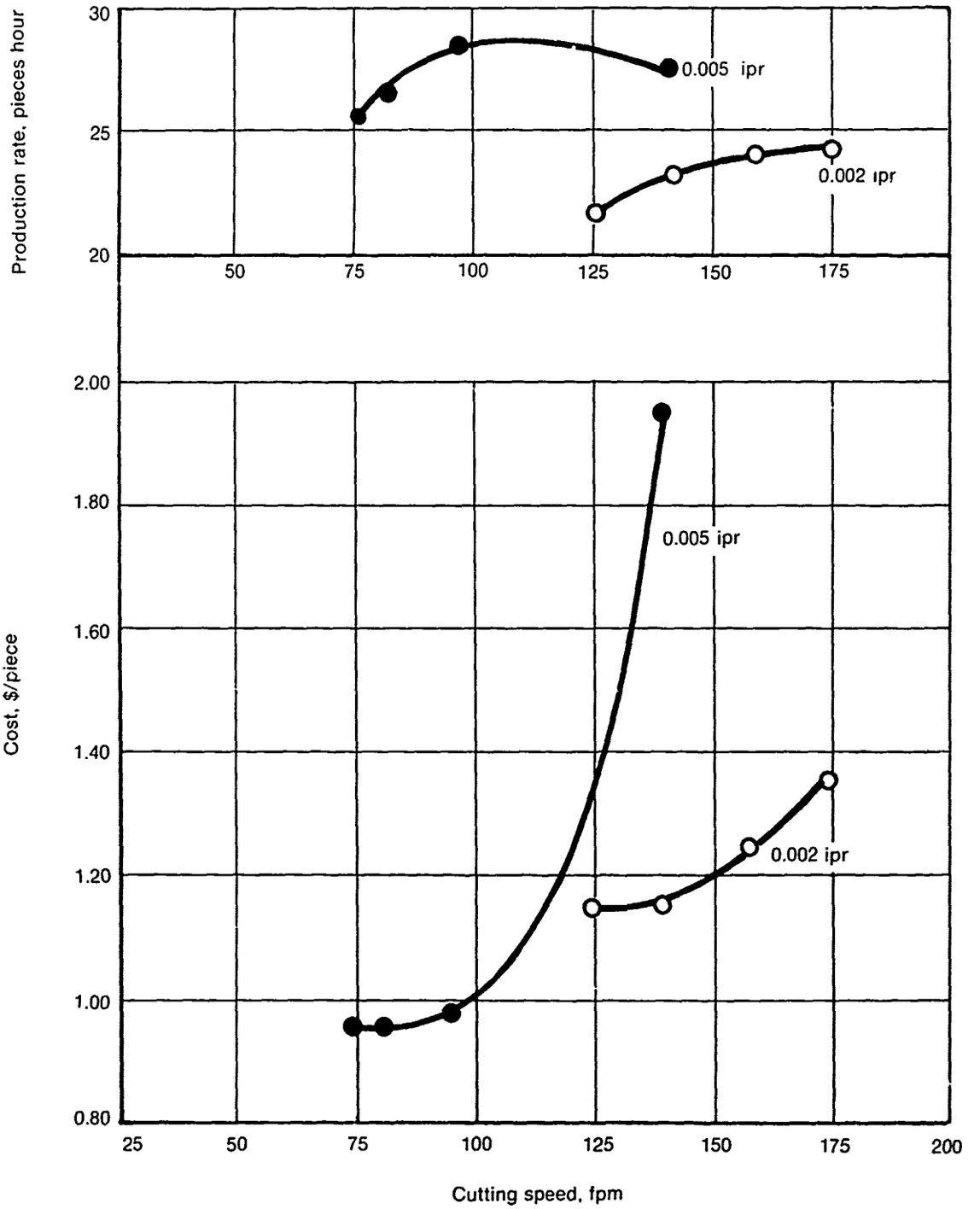


Figure 21–11 Cutting speed versus cost and production rate for drilling holes in 4340 steel (annealed to 212 Bhn) using two feed rates.

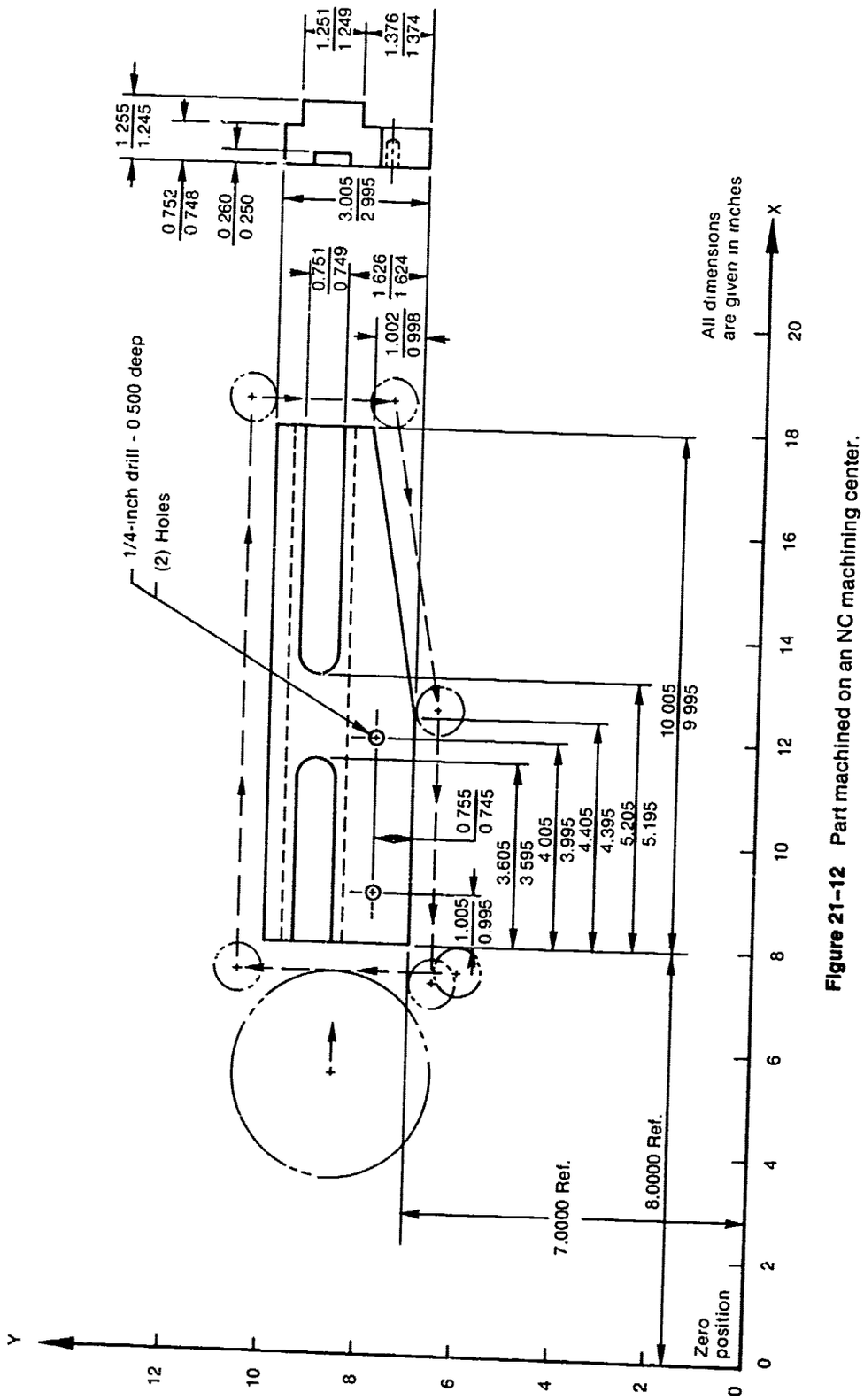


Figure 21-12 Part machined on an NC machining center.

TABLE 21–20 Time Study and Cost Data for Machining 4340 Steel Forging on an NC Machining Center

OPER. NO.	OPERATION	Part No.	456987-003		
N 010	Face mill top surface	Part Name	Bracket—Slider		
N 020	Peripheral end mill sides and ends	Material	AISI 4340 Steel Forg.		
N 030	End mill two slots in top surface	Condition	Normalized		
N 040	Drill (2) 0.250-inch dia. holes	Hardness	331 Bhn		

VARIABLE	DEFINITION	OPERATION NO.			
		N 010	N 020	N 030	N 040
C_c	Cost of each insert or inserted blade; $/blade	3.40	—	—	—
C_p	Purchase cost of tool or cutter; $/cutter	245.00	15.00	10.00	0.80
C_w	Cost of grinding wheel for resharpening tool or cutter; $/cutter	—	0.10	0.10	—
d	Depth of cut, in	0.100	0.250	0.250	—
D	Dia. of tool in milling and drilling; in	4.000	1.000	0.750	0.250
e	Extra travel at feedrate (f_r or f_t) including approach, overtravel, and all positioning moves; in	5.00	5.50	2.25	0.50
f_r	Feed per revolution; in	—	—	—	*
f_t	Feed per tooth; in	*	*	*	—
G	Labor + overhead in tool reconditioning department; $/min	0.40	0.40	0.40	0.40
k_1	No. of times milling cutter or drill is reused before being discarded	9000	7	7	12
k_2	No. of times milling cutter is resharpened before inserts (or blades) are rebrazed (or reset)	—	—	—	—
k_3	No. of times blades (or inserts) are resharpened (or indexed) before blade (or inserts) are discarded	8	—	—	—
L	Length of workpiece in milling or sum of length of all holes of same diameter in drilling; in	10.00	26.25	8.40	1.00
M	Labor + overhead cost of machining center	0.83	0.83	0.83	0.83
N_L	No. of workpieces in lot	20	20	20	20
r	Rapid traverse rate;	150	150	150	150
R	Total rapid traverse distance for a cutter on one part; in	43.00	27.25	46.35	41.00
t_b	Time to rebraze cutter teeth or reset blades; min	—	—	—	—
t_d	Time to replace dull cutter in tool changer storage unit; min	3.0	3.0	3.0	3.0
t_i	Time to index from one type cutter to another between operations (automatic or manual); min	0.1	0.1	0.1	0.1
t_l	Time to load and unload workpiece; min	2.0	2.0	2.0	2.0
t_o	Time to setup machine tool for operation; min	60	60	60	60
t_p	Time to preset tools away from machine (in toolroom); min	20	15	15	12
t_s	Time to resharpen lathe tool, milling cutter, drill, reamer or tap; min/tool	—	15	15	5
T_f	Tool life measured in inches travel of work or tool to dull a drill, reamer, tap or one milling cutter tooth; in	*	*	*	*
v	Cutting speed; fpm	*	*	*	*
w	Width of cut; in	3.50	0.75	0.75	—
Z	No. of teeth in milling cutter or no. of flutes in a tap	6	4	4	—

*These values taken from Tool Life Data, table 21–21.

TABLE 21–21 Tool Life Data for Machining 4340 Steel on an NC Machining Center

FACE MILLING*

MATERIAL	CONDITION AND MICROSTRUCTURE	HARDNESS Bhn	TOOL MATL. Trade Name	TOOL MATL. Industry Grade	UP OR DOWN MILLING	TOOL GEOMETRY AR°	RR°	CA°	TR°	Incl°	ECEA°	End Rel.° / Cor. Rel.°	CUTTING FLUID CODE †	DEPTH OF CUT in	WIDTH OF CUT in	FEED PER TOOTH in	TOOL LIFE END POINT in	TOOL LIFE/TOOTH inches work travel vs CUTTING SPEED, fpm			
Alloy steel 4340	Normalized	320	370	C-6	Up	0	−7	45	−5	5	5	6	00	0.100	4.0	0.005	0.016	① 47	② 70	③ 83	④ 95
	Acicular											6						670	540	445	345

PERIPHERAL END MILLING

MATERIAL	CONDITION AND MICROSTRUCTURE	HARDNESS Bhn	TOOL MATL. Trade Name	TOOL MATL. Industry Grade	CUTTER TYPE	DIA. in	NO. TEETH	FLUTE LENGTH in	UP OR DOWN MILLING	TOOL GEOMETRY Helix Angle°	RR°	Chamfer	ECEA°	End Rel.° / Periph. Rel.°	CUTTING FLUID CODE †	DEPTH OF CUT in	WIDTH OF CUT in	FEED PER TOOTH in	TOOL LIFE END POINT in	TOOL LIFE/CUTTER inches work travel vs CUTTING SPEED, fpm			
Alloy steel 4340	Normalized	331	—	M2 HSS	Solid HSS Double end	0.750	4	2	Down	30	10	45° x 0.060 in	1	3	11 1.20 Flood	0.250	0.750	0.004	0.012	⑤ 50	⑥ 100	⑦ 140	⑧ 220
	Acicular													7						155	100	80	70

END MILL SLOTTING

MATERIAL	CONDITION AND MICROSTRUCTURE	HARDNESS Bhn	TOOL MATL. Trade Name	TOOL MATL. Industry Grade	CUTTER TYPE	DIA. in	NO. TEETH	FLUTE LENGTH in	UP OR DOWN MILLING	TOOL GEOMETRY Helix Angle°	RR°	Chamfer	ECEA°	End Rel.° / Periph. Rel.°	CUTTING FLUID CODE †	DEPTH OF CUT in	WIDTH OF CUT in	FEED PER TOOTH in	TOOL LIFE END POINT in	TOOL LIFE/CUTTER inches work travel vs CUTTING SPEED, fpm			
Alloy steel 4340	Normalized	331	—	M2 HSS	Solid HSS Double end	0.750	4	2	—	30	10	45° x 0.060 in	1	3	11 1:20	0.250	0.750	0.002	0.012	⑨ 50	⑩ 110	⑪ 190	
	Acicular													7						65	54	43	

DRILLING

MATERIAL	CONDITION AND MICROSTRUCTURE	HARDNESS Bhn	DRILL MATL. Trade Name	DRILL MATL. Industry Grade	TYPE DRILL	DRILL SIZE Dia. in	Length in	Flute Length in	DRILL GEOMETRY Type Point	Helix Angle°	Point Angle°	Lip Relief°	CUTTING FLUID CODE †	DEPTH OF HOLE in	FEED ipr	DRILL LIFE END POINT in	DRILL LIFE no. of holes vs CUTTING SPEED, fpm			
Alloy steel 4340	Normalized	331	—	M1 HSS	Twist	0.250	2.5	1.375	Standard	29	118	7	11 1:20	0.5 thru	0.002	0.015	⑫ 20	⑬ 50	⑭ 100	⑮ 160
	Acicular																90	74	60	50
"	"	"	—	"	"	"	"	"	"	"	"	"	"	"	0.005	"	⑯ 10	⑰ 50	⑱ 100	⑲ 160
	"																74	45	36	30

*Single tooth cutter except as noted

† Cutting Fluid Code
00 Dry
11 Soluble Oil

N/C MACHINING COSTS AND OPERATION TIMES
FOR
PART NO.-456987-003 * PART NAME-BRACKET-SLIDER * LOT SIZE- 20
MATERIAL-AISI 4340 STEEL,NORMALIZED,ACICULAR * HARDNESS- 331

DATA SET NO.	OPER NO.	MACHG OPER.	TOOL MATL	SPEED SFM	FEED	TOOL LIFE	FEED COST $	RAPD TRAV $	LOAD UNLD $	SET UP $	TOOL INDX $	TOOL REPL $	TOOL DEPR $	TOOL SHPN $	BLAD RSET $	INST COST $	GRND WHL $	TOOL PRST $	TOTAL COST $	OPER. TIME MIN.
30001	N010	FM-TA	C-6	670.	0.005	47.	0.65	0.24		0.08	0.09	0.00			0.09		0.28		1.43	1.27
30002	N010	FM-TA	C-6	540.	0.005	70.	0.80	0.24		0.08	0.06	0.00			0.06		0.19		1.44	1.43
30003	N010	FM-TA	C-6	445.	0.005	83.	0.98	0.24		0.08	0.05	0.00			0.05		0.16		1.56	1.62
30004	N010	FM-TA	C-6	345.	0.005	95.	1.26	0.24		0.08	0.04	0.00			0.04		0.14		1.81	1.96
30005	N020	EM-HSS	M2	155.	0.004	50.	2.78	0.15		0.08	0.33	0.25	0.79			0.01	0.79		5.18	4.03
30006	N020	EM-HSS	M2	100.	0.004	100.	4.31	0.15		0.08	0.16	0.12	0.39			0.01	0.39		5.63	5.67
30007	N020	EM-HSS	M2	80.	0.004	140.	5.39	0.15		0.08	0.12	0.09	0.28			0.00	0.28		6.40	6.92
30008	N020	EM-HSS	M2	70.	0.004	220.	6.16	0.15		0.08	0.07	0.06	0.18			0.00	0.18		6.88	7.79
30009	N030	EM-HSS	M2	65.	0.002	50.	3.34	0.26		0.08	0.10	0.05	0.25			0.00	0.25		4.34	4.56
30010	N030	EM-HSS	M2	54.	0.002	110.	4.02	0.26		0.08	0.05	0.02	0.11			0.00	0.11		4.66	5.31
30011	N030	EM-HSS	M2	43.	0.002	190.	5.05	0.26		0.08	0.03	0.01	0.07			0.00	0.07		5.56	6.52
30012	N040	DRILL	M1	90.	0.002	10.	0.45	0.23		0.08	0.25	0.01	0.20				0.48		1.70	1.22
30013	N040	DRILL	M1	74.	0.002	25.	0.55	0.23		0.08	0.10	0.00	0.08				0.19		1.23	1.16
30014	N040	DRILL	M1	60.	0.002	50.	0.68	0.23		0.08	0.05	0.00	0.04				0.10		1.18	1.25
30015	N040	DRILL	M1	50.	0.002	80.	0.81	0.23		0.08	0.03	0.00	0.02				0.06		1.24	1.39
30016	N040	DRILL	M1	74.	0.005	5.	0.22	0.23		0.08	0.50	0.01	0.40				0.96		2.40	1.24
30017	N040	DRILL	M1	45.	0.005	25.	0.36	0.23		0.08	0.10	0.00	0.08				0.19		1.05	0.93
30018	N040	DRILL	M1	36.	0.005	50.	0.45	0.23		0.08	0.05	0.00	0.04				0.10		0.95	0.98
30019	N040	DRILL	M1	30.	0.005	90.	0.54	0.23		0.08	0.03	0.00	0.02				0.05		0.96	1.06
LOAD, UNLOAD AND SETUP TIME AND COST									1.66	2.49									4.15	5.00

NOTE - FEED UNITS ARE IPR FOR TURNING, DRILLING,REAMING, AND CENTERDRILLING OR CHAMFERING
FEED UNITS ARE IPT FOR MILLING
TOOL LIFE UNITS ARE IN, FOR MILLING, DRILLING, REAMING,AND TAPPING
TOOL LIFE UNITS ARE MIN. FOR TURNING
TOOL LIFE UNITS ARE NO. OF HOLES FOR CENTERDRILLING OR CHAMFERING

Figure 21–13 Printout of cost and production rate results for machining 4340 steel forging on an NC machining center.

N/C MACHINING COSTS AND OPERATION TIMES
FOR
PART NO.-456987-003 * PART NAME-BRACKET-SLIDER * LOT SIZE- 20
MATERIAL-AISI 4340 STEEL,NORMALIZED,ACICULAR * HARDNESS- 331

DATA SET NO.	OPER NO.	MACHG OPER.	TOOL MATL	SPEED SFM	FEED	TOOL LIFE	FEED COST	RAPD TRAV	LOAD UNLD	SET UP	TOOL INDX	TOOL REPL	TOOL DEPR	TOOL SHPN	BLAD RSET	INST COST	GRND WHL	TOOL PRST	TOTAL COST $	OPER. TIME MIN.
30001	NO10	FR-TA	C-6	670.	0.005	47.	0.65	0.24		0.08	0.09	0.00			0.09		0.28	1.43	1.27
30005	NO20	EM-HSS	M2	155.	0.004	50.	2.78	0.15		0.08	0.33	0.25	0.79			0.01	0.79	5.18	4.03
30009	NO30	EM-HSS	M2	65.	0.002	50.	3.34	0.26		0.08	0.10	0.05	0.25			0.00	0.25	4.34	4.56
30018	NO40	DRILL	M1	36.	0.005	50.	0.45	0.23		0.08	0.05	0.00	0.04				0.10	0.95	0.98
LOAD, UNLOAD AND SETUP TIME AND COST									1.66	2.49								4.15	5.00
							7.22	.88	1.66	2.49	.32	.57	.30	1.08	.09	.01	1.42	16.05	15.84

NOTE - FEED UNITS ARE IPR FOR TURNING, DRILLING,REAMING, AND CENTERDRILLING OR CHAMFERING
FEED UNITS ARE IPT FOR MILLING
TOOL LIFE UNITS ARE IN, FOR MILLING, DRILLING, REAMING,AND TAPPING
TOOL LIFE UNITS ARE MIN. FOR TURNING
TOOL LIFE UNITS ARE NO. OF HOLES FOR CENTERDRILLING OR CHAMFERING

Figure 21–14 Best conditions for machining 4340 steel forging on an NC machining center.

TABLE 21–22 Optimized Cutting Speed Equations for Use with English Units

For Turning

$$V_{min.\ cost} = S\left[\frac{nM(L+e)}{L(1-n)\left(Mt_d + \frac{C_p}{k_1+1} + Gt_s + \frac{Gt_b}{k_2} + \frac{C_c}{k_3} + C_w + Gt_p\right)}\right]^n$$

$$V_{max.\ prod} = S\left[\frac{n(L+e)}{(1-n)Lt_d}\right]^n$$

For Milling

$$V_{min.\ cost} = (S_t)^{\frac{1}{n+1}}\left[\frac{nMD(L+e)}{3.82f_t L\left(Mt_d + \frac{C_p}{k_1+1} + Gt_s + \frac{Gt_b}{k_2} + \frac{ZC_c}{k_3} + C_w + Gt_p\right)}\right]^{\frac{n}{n+1}}$$

$$V_{max.\ prod.} = (S_t)^{\frac{1}{n+1}}\left[\frac{nD(L+e)}{3.82f_t Lt_d}\right]^{\frac{n}{n+1}}$$

For Drilling or Reaming

$$V_{min.\ cost} = (S_t)^{\frac{1}{n+1}}\left[\frac{nMD(L+e)}{3.82f_r L\left(Mt_d + \frac{C_p}{k_1+1} + Gt_s + Gt_p\right)}\right]^{\frac{n}{n+1}}$$

$$V_{max.\ prod.} = (S_t)^{\frac{1}{n+1}}\left[\frac{nD(L+e)}{3.82f_r Lt_d}\right]^{\frac{n}{n+1}}$$

For Tapping

$$V_{min.\ cost} = (S_t)^{\frac{1}{n+1}}\left[\frac{mnMD(L+e)}{1.91L\left(Mt_d + \frac{C_p}{k_1+1} + Gt_s + Gt_p\right)}\right]^{\frac{n}{n+1}}$$

$$V_{max.\ prod.} = (S_t)^{\frac{1}{n+1}}\left[\frac{mnD(L+e)}{1.91Lt_d}\right]^{\frac{n}{n+1}}$$

TABLE 21-23 Optimized Cutting Speed Equations for Use with Metric Units

For Turning

$$V_{min.\ cst} = 3\left[\frac{nM(L+e)}{L(1-n)\left(Mt_d + \frac{C_p}{k_1+1} + Gt_s + \frac{Gt_b}{k_2} + \frac{C_s}{k_3} + C_w + Gt_p\right)}\right]^n$$

$$V_{max.\ prod.} = 3\left[\frac{n(L+e)}{(1-n)Lt_d}\right]^n$$

For Milling

$$V_{min.\ cst} = (S_t)^{\frac{1}{n+1}}\left[\frac{nMD(L+e)}{318f_t L\left(Mt_d + \frac{C_p}{k_1+1} + Gt_s + \frac{Gt_b}{k_2} + \frac{ZC_s}{k_3} + C_w + Gt_p\right)}\right]^{\frac{n}{n+1}}$$

$$V_{max.\ prod.} = (S_t)^{\frac{1}{n+1}}\left[\frac{nD(L+e)}{318f_t Lt_d}\right]^{\frac{n}{n+1}}$$

For Drilling or Reaming

$$V_{min.\ cst} = (S_t)^{\frac{1}{n+1}}\left[\frac{nMD(L+e)}{318f_t L\left(Mt_d + \frac{C_p}{k_1+1} + Gt_s + Gt_p\right)}\right]^{\frac{n}{n+1}}$$

$$V_{max.\ prod.} = (S_t)^{\frac{1}{n+1}}\left[\frac{nD(L+e)}{318f_t Lt_d}\right]^{\frac{n}{n+1}}$$

For Tapping

$$V_{min.\ cst} = (S_t)^{\frac{1}{n+1}}\left[\frac{nMD(L+e)}{159pL\left(Mt_d + \frac{C_p}{k_1+1} + Gt_s + Gt_p\right)}\right]^{\frac{n}{n+1}}$$

$$V_{max.\ prod.} = (S_t)^{\frac{1}{n+1}}\left[\frac{nD(L+e)}{159pLt_d}\right]^{\frac{n}{n+1}}$$

TABLE 21–24 Optimized Tool Life Equations for Use with English or Metric Units

For Turning

$$T_{\text{min. cost}} = \left[\frac{S}{V_{\text{min. cost}}}\right]^{\frac{1}{n}}$$

$$T_{\text{max. prod.}} = \left[\frac{S}{V_{\text{max prod}}}\right]^{\frac{1}{n}}$$

For Milling, Drilling, Reaming or Tapping

$$T_{t\ \text{min. cost}} = \left[\frac{S_t}{V_{\text{min cost}}}\right]^{\frac{1}{n}}$$

$$T_{t\ \text{max prod.}} = \left[\frac{S_t}{V_{\text{max. prod.}}}\right]^{\frac{1}{n}}$$

TURNING INSERTS — COST & PRODUCTION
MACHINABILITY DATA CENTER PROGRAM

STEP	HP-67/97		KEYS	OUTPUT
1	Load Strip			
2	Initialize		RTN R/S	3.00†
3	Load-Unload Time	min	ENTER	
	Index Time	min	ENTER	
	Rapid Trav Dist	in	ENTER	
	Rapid Trav Rate	in/min	R/S	4.00†
4	Insert Cost	$	ENTER	
	# Cutting Edges		ENTER	
	Set-up Time	min	ENTER	
	# Pieces in Lot		R/S	5.00†
5	Preset Cost	$	ENTER	
	Overhead	$/min	ENTER	
	Dull Tool Rep Time	min	R/S	6.00†
6	Diam Work	in	ENTER	
	Extra Travel	in	ENTER	
	Length of Cut	in	R/S	7.00†
7	Tool Life	min	ENTER	
	Speed	fpm	ENTER	
	Feed	ipr	R/S	PTS/TL§
8	for Times		CF 1	
	or for Costs		SF 1	
9	Constant (cost or time)		A	$orMin
	Feeding (cost or time)		B	$or Min
	Tool (cost or time)		C	$orMin
	Total (cost or time)		D	$orMin
*	for New Tool Life, V&F		E	7.00†
*	for New Geometry		GTO 6 R/S	6.00†

†These prompting outputs give the numbers of the next step to be executed

§This is the output of the number of parts that can be machined with one edge of one insert

1. *Select the proper magnetic strip and insert it into the calculator*
2. *Initialize*
3. *Enter data and press appropriate keys*

2.3	
0	
27.2	
100.	
3.15	
8.	
21.	
20.	
0	
.40	
.4	
3.5	
.2	
19.	
60.	
325.	
.01	
11.2	Parts per edge

4. *Execute steps 8 and 9 for output*

Cost ($)	Prod Time (min)
1.45	3.62
2.17	5.41
.05	.04
3.67	9.07

5. *Loop back using * steps if desired*

Figure 21–15 Instructions and sample inputs and outputs for cost and production calculations using the HP-67 calculator.

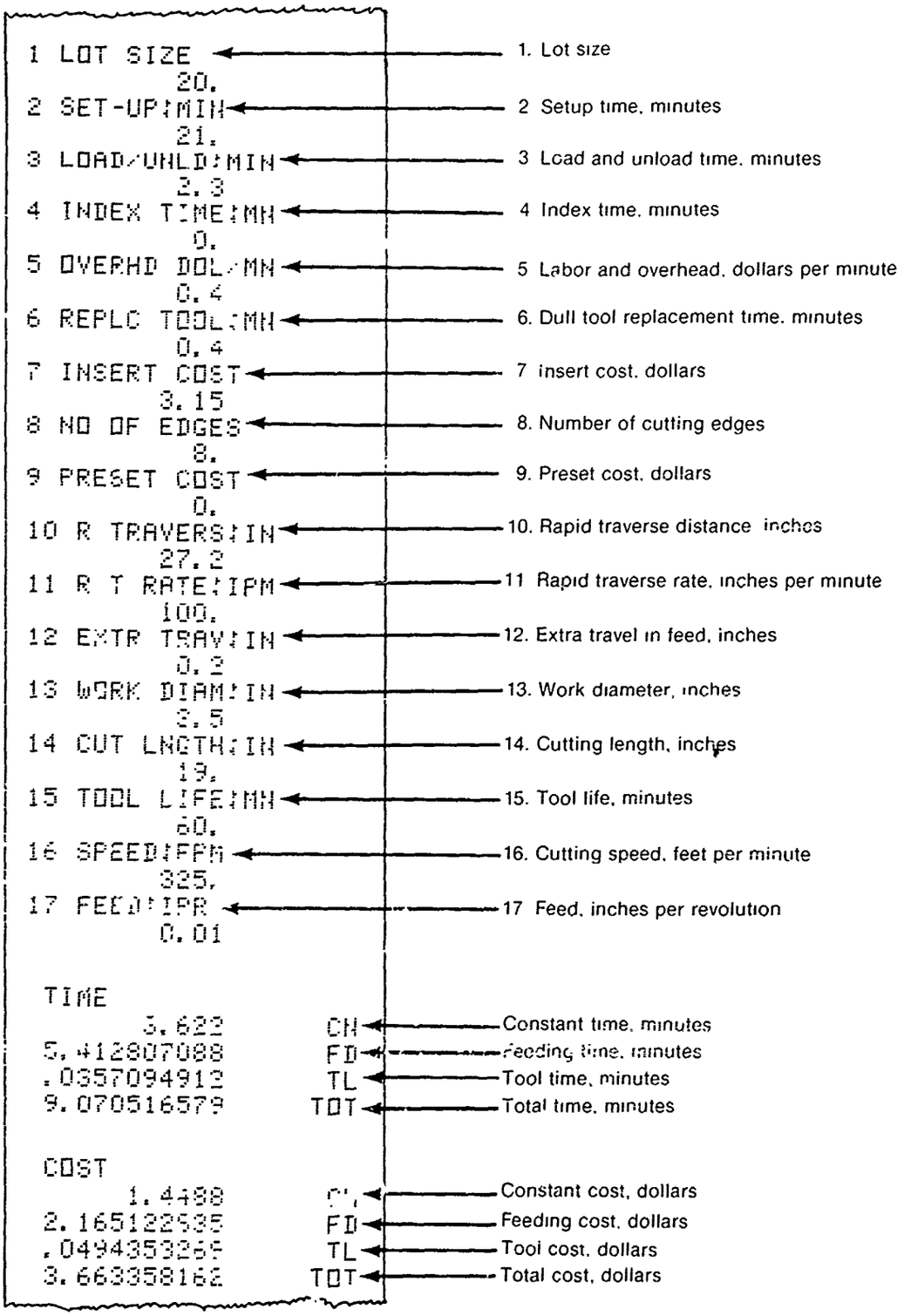


Figure 21–16 Example of the cost and production program as run on the .9 calculator.

SECTION 22

MACHINE CHATTER AND VIBRATION

Introduction 22–3
Causes of Vibration 22–3
Damping 22–5
Responses of Structures to Periodic Forces 22–6
Self-Excited Chatter 22–12
Troubleshooting Chatter 22–17
Regenerative Chatter Checklist 22–22

NOTE: The material in this section was adapted in large part from a home-study course and reference manual entitled "How to Troubleshoot Machine Chatter and Vibration" with permission of Manufacturing Education Copyright 1978 by Manufacturing Education, P O. Box 36050, Cincinnati, Ohio 45236

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MACHINE CHATTER AND VIBRATION 22

INTRODUCTION

Problems arising from machine tool-workpiece vibration are among the major obstacles to greater productivity in metal cutting. The vibratory motion between a cutting tool and a workpiece is recorded on the workpiece surface and, depending upon the severity of the oscillatory motion and the surface finish specifications, may result in parts with unsatisfactory surface quality. Excessive vibration or chatter may also seriously decrease tool life. In addition, chatter affects the life of bearings and other machine components, although this is not well understood.[1-4]

Higher production rates and more severe cutting conditions encountered in modern shops reveal another vibration problem—excessive noise. This problem usually stems from the high frequency vibrational condition known as chatter, and while it may have only a slight physical effect on surface finish, recent government regulations have focused sharply upon the noise environment of the machine tool operator.

It is necessary to solve a vibration problem if unsatisfactory tool life, surface finish, or noise result. Many experienced shop people are aware of chatter and vibration, but few have the training to identify the types of vibration problems and the appropriate methods for their solution. The discussion that follows provides an understanding of the causes of machine tool-workpiece vibration problems and alternative approaches for their elimination.

CAUSES OF VIBRATION

Deflection of Machine Elements

In order to analyze vibration problems, it is important first to understand the deflection characteristics of materials. The most important material property governing deflection is the modulus of elasticity. For most structures, the amount of elastic, nonpermanent, deflection for a given load is inversely proportional to the modulus of elasticity. Thus, a higher modulus will result in a lower deflection. Table 22-1 gives the modulus of elasticity of materials commonly used in machine tools, tooling, and fixturing.

TABLE 22-1 Modulus of Elasticity of Some Common Materials

MATERIAL	MODULUS OF ELASTICITY, E (psi)
Aluminum	9,000,000
Cast iron	14,000,000 (varies widely)
Steel	29,000,000
Tungsten carbide	86,000,000

It is important to note that all steels, regardless of alloy content, heat treatment or hardness, have approximately the same modulus of elasticity. The elastic modulus depends on the fundamental atomic structure of the material, while strength and hardness are very dependent on small percentages of elements which do not affect the modulus. Of the materials listed in table 22-1, aluminum is the poorest material for minimizing the deflection of machine structures. Cast iron is more resistant to deflection than aluminum, steel is even better, and tungsten carbide is superior. Since cast iron is an easily obtainable material and less expensive to machine than steel, it is often used in machine tool structures in spite of its lower modulus of elasticity. Tungsten carbide is very expensive and costly to machine, hence, it is used where performance is more important than cost.

For a given material, the deflection of a structure is a function of the applied load and the geometry. Equation 22-1 can be used to predict the deflection of the cantilever beam with a round cross section, illustrated in figure 22-1.

$$d = \frac{64PL^3}{3\pi ED^4} \qquad \text{(Eq. 22-1)}$$

where:

- d = beam deflection, inches
- P = force on the end of the beam, pounds
- L = length of the beam, inches
- D = beam diameter, inches
- E = modulus of elasticity, pounds per square inch

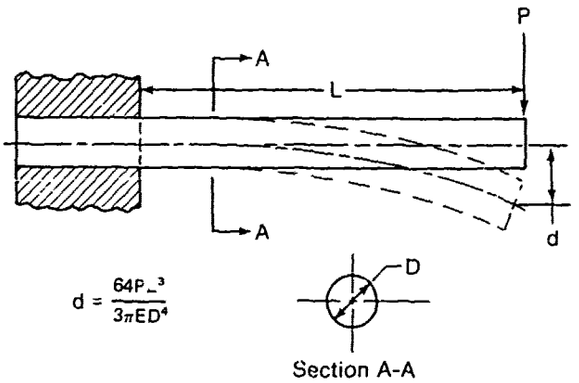


Figure 22-1 Deflection of a cantilever beam.

Equation 22-1 only applies "exactly" to a slender beam solidly held on one end by a massive base. However, it can be used to approximate the deflection of a boring bar extending from a tool post or tool holder, a slender workpiece sticking out of a vise, a spindle nose extending beyond its front bearings, or any "slender" beam or "thin" plate that projects for some unsupported distance. In this case, "slender" and "thin" are relative terms and may refer to some very heavy cross sections that have an unsupported length several times their thickness. In equation 22-1, the beam diameter (D) is raised to the fourth power and the beam length (L) to the third power, implying that both are very important quantities influencing beam deflection.

For a given beam, a given percentage increase in overhang length (L) produces a much greater percentage increase in deflection. For example, a doubling of beam length results in an eight-fold increase in deflection. Thus in tooling and fixture design, an absolute minimum of overhang should be used. Boring bar design is an example where a length-to-

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diameter ratio of greater than four or five to one is considered impractical A given percentage increase in diameter (D) has an even greater effect on reducing deflection than length had on increasing deflection; hence, it is important to have the diameter of overhanging members as large as possible

Structural Stiffness

The stiffness of a structure can be interpreted as the amount of force required to produce an inch of deflection Equation 22-2 can be used to calculate the stiffness of a structure in pounds per inch.

$$K = \frac{P}{d} \qquad \text{(Eq 22-2)}$$

where:

K = stiffness, pounds per inch
P = force, pounds
d = deflection, inches

For example, if a machine deflects 0.001 inch under a load of 800 pounds, the stiffness is:

$$K = \frac{800}{0.001} = 800{,}000 \text{ lb/in}$$

If the stiffness of a structure is known, its deflection under load can be calculated from a modified form of equation 22-2:

$$d = \frac{P}{K}$$

The term "directional stiffness" is used to describe the stiffness of a structure when loaded in different directions. This is an important concept because many machines, tools, and workpieces have both stiff and weak directions. If a machining setup is made so that cutting forces are aimed toward the weak direction, excessive deflection and possible chatter will occur. If the setup is changed so that the forces are in the stiff direction, the problem will be minimized or eliminated. As an example, consider figure 22-2: if this beam is loaded in the Z or the X directions, it will be very rigid. Loading the beam in the Y direction produces the greatest deformation and, therefore, the lowest directional stiffness.

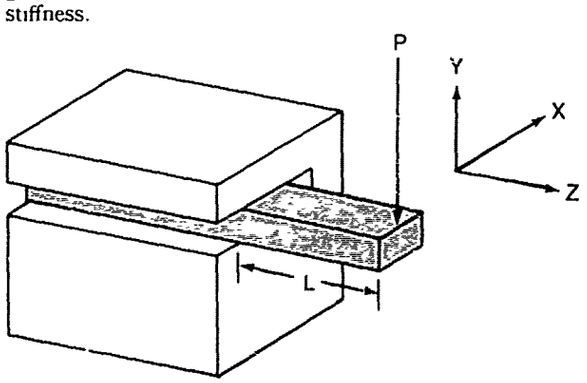


Figure 22-2 Illustration of the concept of directional stiffness. For this beam the stiff directions are X and Z; the weak direction is Y.

Forcing of Structures

The important terminology of vibration a· ·sis is illustrated in figure 22-3 and is used extensively in the following discussion Included are:

Amplitude, A, is the maximum displacement from the equilibrium position It is one-half of the peak-to-valley distance and is *not* the total displacement from the topmost peak to the lowest valley

Period, T, is the time required to complete one full cycle of vibration.

Frequency, f, is the number of cycles which are completed in a given amount of time, usually one second.

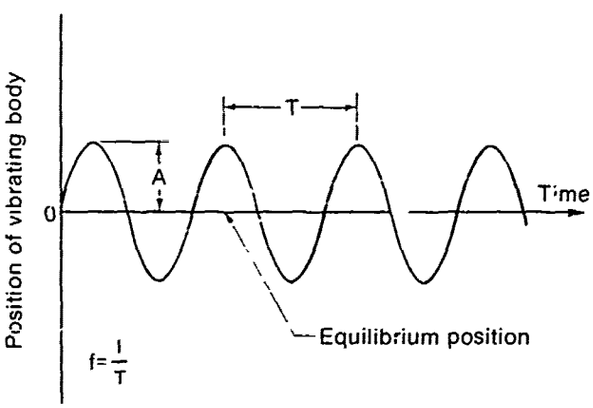


Figure 22-3 Periodic motion of a vibrating structure.

Equation 22-3 is an important relationship between frequency and period:

$$f \text{ (cycles per second)} = \frac{1}{T \text{ (sec)}} \qquad \text{(Eq. 22-3)}$$

Another name for "cycles per second" is Hertz. For example, 20 cycles per second is the same as 20 Hertz. While the term Hertz is the official standard for frequency in the U. S. A., many prefer to use the more descriptive term cycles per second, or cps. The term cps will be used in this discussion.

Most people are familiar with things that start vibrating by giving them a push and letting go. If the "structure" vibrates, it does so at a frequency determined by the structure itself, not by the force or displacement given it. The initiation of vibration in machine tools is often by forces that fluctuate periodically, that is, by forces that vary with time. The structure is said to be "excited" by the fluctuating force. Motor unbalance is a common method by which periodic forces in machinery are introduced. Another example of periodic forces in machining is the variation in cutting forces introduced by cutting through a keyway contained in a shaft. The cutting force will drop to zero each time the tool tip enters the keyway and return to its nominal value after the tool re-enters the workpiece.

The occurrence of forced vibrations in a milling operation can be expected for three major reasons First, the number of teeth in contact with the workpiece is changing constantly Second, the angular orientation of the force changes as the tooth rotates. Third, the chip thickness changes as the tooth moves through the arc of contact. Figure 22-4 is an illustration of an actual recording of milling forces [1] Forced vibration is obviously present in all three cutting force components. F_x, F_y, and F_z

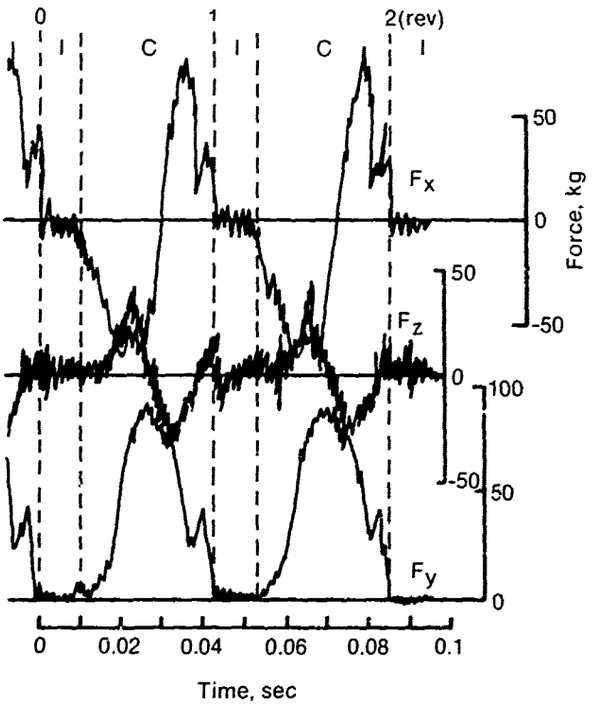


Figure 22-4 Fluctuation of the cutting force components in a milling operation. (Adapted from Hosoi[14])

DAMPING

Damping is the behavior of a system that tends to resist rapid movements. If a beam is struck with a hammer and vibrates for a long time, it is said to be lightly damped. If the beam stops vibrating almost immediately, it is said to be highly damped. Theoretically, a system that had no damping would go on vibrating forever, at the same initial amplitude. This can not occur in practice because all materials have some amount of internal damping Because of the basic way in which materials deform, all of the work that is done to deflect an elastic member can not be recovered when the member is released. Most of the energy is recovered, but a small amount remaining in the member is converted into heat. This small energy loss causes the vibration amplitude to decrease very slightly each cycle.

Different materials have different amounts of internal damping. Figure 22-5 illustrates the different damping characteristics of cast iron and steel and shows clearly that cast iron has much higher internal damping This figure might lead to the conclusion that cast iron machine structures have a much better vibration resistance than those built from steel

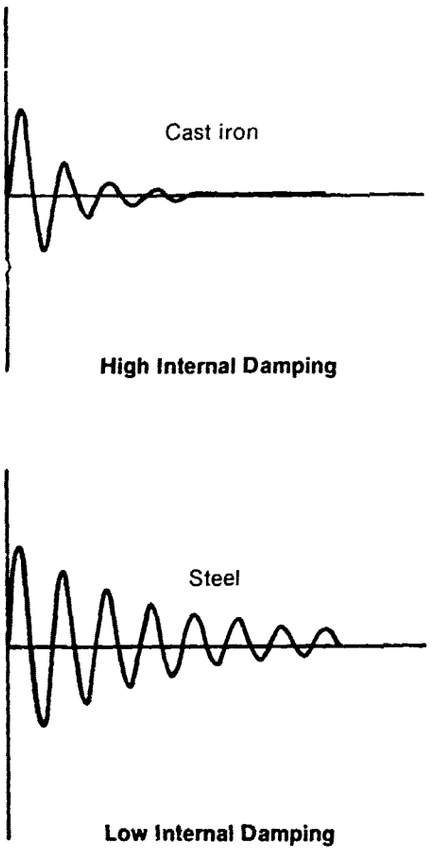


Figure 22-5 Diagrams showing the difference in internal damping of cast iron and steel.

Material damping, however, is not the whole story because joint damping, or "squeeze film" damping, is also very important in machinery. Oil becomes trapped between mating surfaces that move apart during vibration. Oil is sucked in and fills the gap as surfaces move apart and is forced out when they close. This motion of the oil heats it, absorbing energy. While this is the most powerful source of damping in joints, some damping takes place in dry joints as a result of friction and the squeezing of air in and out. This damping is generally much less significant, however.

Figure 22-6 illustrates that the damping of a machine increases as components are added to it Most of the damping in the completed machine results from the joints between the various components, rather than from the internal damping of the structural components

The third major category of damping is that intentionally added to a machine to improve its resistance to vibration. A common, non-metalcutting example of this is the automobile shock absorber. Similarly, tuned damped vibration absorbers provide a convenient way to improve the vibration resistance of many machine tools.

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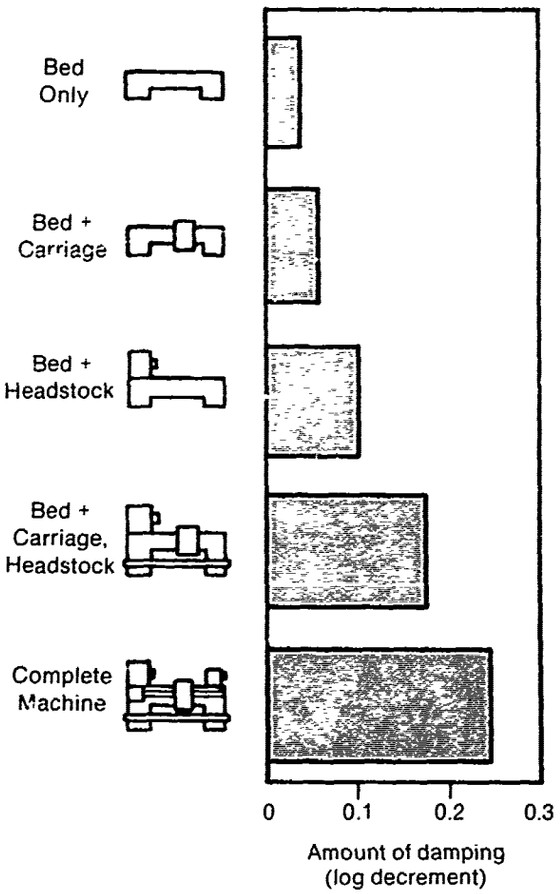


Figure 22-6 Influence of material and of joints on damping. (Adapted from Peters[5])

RESPONSES OF STRUCTURES TO PERIODIC FORCES

Static and Dynamic Stiffness

The analysis of the behavior of structures under dynamic loads is far more complicated than that of structural behavior under steady loads The basic principle is that at very low frequencies the structure responds to dynamic loads the same as it does to static loads To emphasize this, consider figure 22-7 which shows the deflection versus static load behavior of a cantilever beam.

This graph could be computed from the deflection equation for a specific beam at various loads. At 100 pounds, the deflection is 0.015 inch; at 200 pounds, it is 0.030 inch, etc. The static stiffness, K, is the value of steady force acting on the structure divided by the deflection it produces. The static stiffness of the beam producing the data of figure 22-7 is 6,670 pounds per inch as shown by the following calculation:

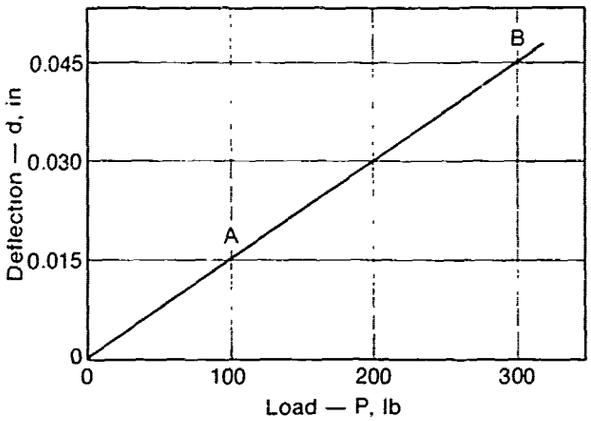


Figure 22-7 Deflection versus static load behavior of a cantilever beam.

$$K = \frac{300}{0.045} = 6670 \text{ lb/in}$$

Note that any load along the line in figure 22-7 divided by the corresponding deflection gives this same value of static stiffness.

Suppose a load that varies from 100 to 300 pounds is applied to the beam. (The peak-to-valley variation in load is 300 − 100 = 200 pounds. The force amplitude is half of the peak-to-valley value, or 100 pounds.) Suppose the frequency of load application is one cycle every two hours, or 0.00014 cycles per second. This is so slow that vibration analysis is not necessary to predict what will happen. The force and deflection will creep slowly up and down the static deflection curve between points A and B in figure 22-7. At any point in time, the value of the deflection for the varying force acting at that instant will be the same as the value of the deflection if the force were static.

If the force variation is increased to one cycle per minute, the speed is still so slow that the bar does not know that it is being vibrated. If the force variation is increased to one cycle per second, or even faster, it is not obvious that the results will be the same. In order to understand what happens at higher frequencies of force variation, it is necessary to introduce the concept of dynamic stiffness. Dynamic stiffness, K_d, is the ratio of the force amplitude, F, to the vibration amplitude, A, at a certain vibration frequency. $K_d = K$; that is, the dynamic and static stiffnesses are the same.

The concept of dynamic stiffness, K_D, can be understood from the curve of figure 22-7 showing load versus deflection. For the example illustrated in figure 22-7, where a peak-to-valley force of 200 pounds (F = 100 pounds) gave a peak-to-valley displacement of 0.045 − 0.015 = 0.030 inch (A = 0.015 inch), the dynamic stiffness is

$$K_d = \frac{100}{0.015} = 6670 \text{ lb/in}$$

where:

F = force amplitude (the maximum increase in the oscillatory force from its average value, that is one half of its peak-to-valley value)

A = vibration amplitude.

Note that this is exactly the same as the value of K, illustrating the fact that as long as the force and displacement data fall on the same curve, their ratios remain the same and the dynamic stiffness is the same as the static stiffness.

Figure 22-8 shows the force pattern acting on a structure at a low frequency and the resulting motion of the structure. This illustrates a very basic point of vibration troubleshooting: namely, *the structure almost always vibrates at the same frequency as the periodic force that is causing it to vibrate.* In figure 22-8 there is a "phase difference" between the two waves: that is, the peaks of the displacement trace occur slightly later than those of the force trace. In spite of this, the period, T, is the same for both waves and consequently the frequency must be the same.

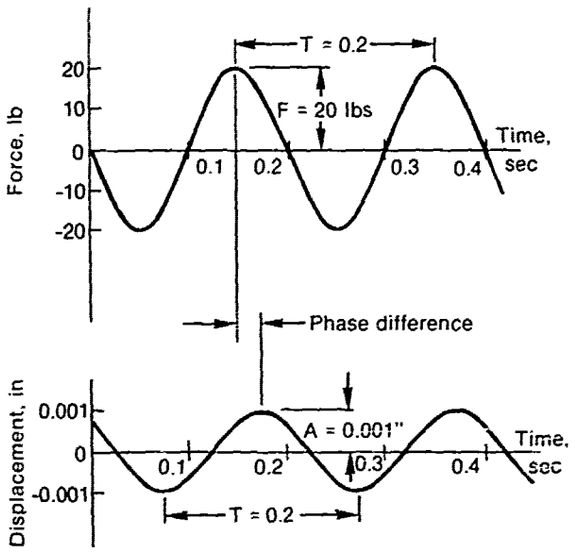


Figure 22-8 Representative force and displacement patterns of a structure vibrating at a low frequency.

There are a few rare cases of unusual structures and unusual force wave shapes where the above relationship between displacement and force is not true, but these cases require an expert to analyze. For purposes of investigating common vibration problems, always proceed as though this rule (italicized above) were true, because it will lead to the best approach to the problem: namely, measure the vibration frequency and look for possible sources of forcing at that same frequency.

Behavior of Simple Structures

Suppose a heavy object is suspended from a weak spring and the upper end of the spring is held in someone's hand. Further suppose the hand is moved up and down, very slowly at first, then at higher and higher frequencies. Let us examine what happens to the heavy object. It would be observed first that the heavy object always moves at the same frequency as the hand. This is elementary, but important. It suggests that when there is a suspected forced vibration problem the cause of the problem can be tracked down by knowing its frequency.

At very low frequencies the heavy object moves exactly the same distance as the hand. Thus, the amplitude of the hand and object are the same and there is no additional stretch in the spring. This behavior is typical of all structures. As the frequency increases, the spring begins to stretch and the amplitude of the object becomes larger than that of the hand. Eventually a frequency is reached where a given hand movement results in a very large object amplitude This condition is called resonance. The frequency where resonance occurs is called the natural frequency, f_n, which is also the frequency at which the dynamic stiffness is the lowest. As the frequency is increased beyond the natural frequency, the amplitude of the object continually decreases until finally the hand can shake very rapidly while the object appears to remain motionless.

It may be concluded from these observations that a machine structure will vibrate easily if it is forced at frequencies near its natural frequency. It will hardly vibrate if forced at a frequency well above the natural frequency. At frequencies well below the natural frequency, the structure will vibrate at some intermediate amplitude. The natural frequency of a simple structure, such as a heavy object suspended on a spring, can be calculated from equation 22-4.

$$f_n = \frac{9.8}{\pi} \sqrt{\frac{K}{W}} \qquad \text{(Eq. 22-4)}$$

where:

f_n = natural frequency, cycles per second
K = spring stiffness, pounds per inch
W = object weight, pounds

When troubleshooting vibration problems, equation 22-4 is seldom used to estimate the natural frequency; however, it is useful for estimating the effects of changes in stiffness and weight.

Behavior of Complex Structures

Figures 22-9 and 22-10 show respectively a motor on its mounting bracket and its frequency response. The system has a static stiffness of 8,330 pounds per inch and a natural frequency of 20 cycles per second. In frequency analysis, it is common to plot the compliance, which is the reciprocal of the static stiffness. Figure 22-11 represents the frequency response of a machine column having a stiffness of 50,000 pounds per inch and a natural frequency of 50. If the bracket of figure 22-9 is attached to this column, the frequency response of the bracket mounted on the column will contain the natural frequency of both the bracket and the column. A composite frequency response can be constructed using simple logic. At low frequencies the motion of the weak bracket is much greater than that of the stiff column. Therefore, up to the lowest natural frequency, only bracket deflection occurs and the composite response

22 MACHINE CHATTER AND VIBRATION

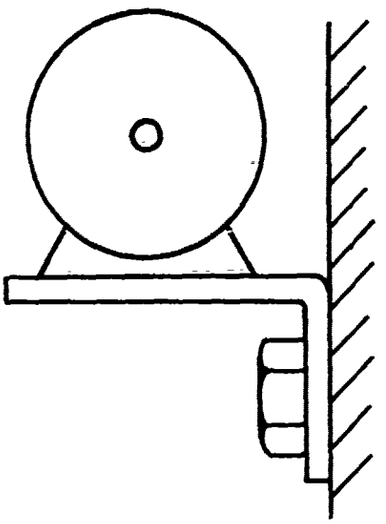


Figure 22-9 Schematic diagram of a motor mounted on a bracket.

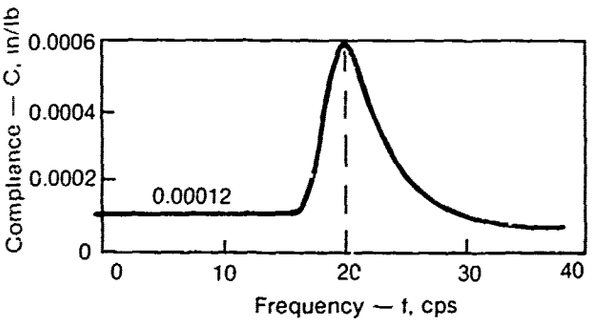


Figure 22-10 Frequency response of the system shown in figure 22-9.

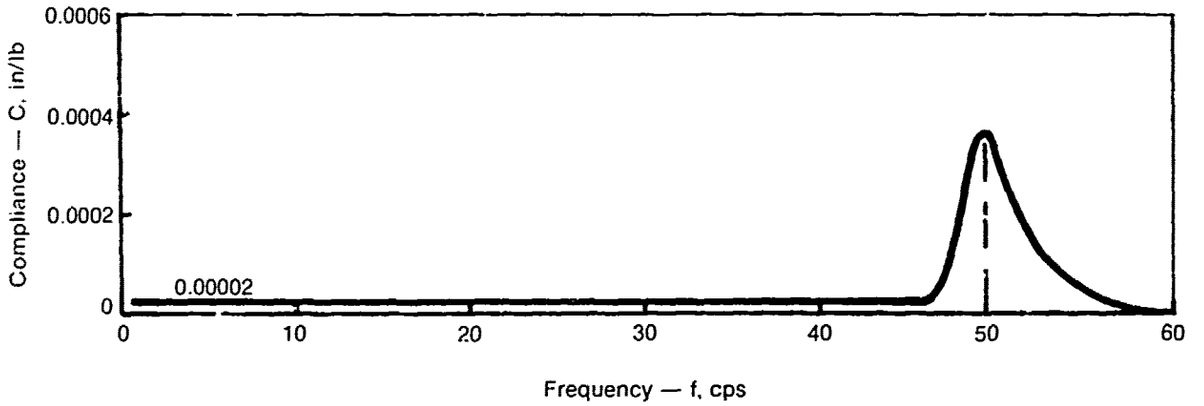


Figure 22-11 Frequency response of a machine column.

curve will be identical to the bracket response curve. At the resonance of the bracket, both the motor and bracket will be vibrating and forcing the column. However, since the motion of the column is still very low at this frequency, the combined frequency response will still be the same as the bracket response through its resonance. The frequency response of the bracket-column will continue to be equal to the frequency response of the bracket alone, until the forcing frequency is close to the column resonance. At this frequency, and at higher frequencies, the column response is much greater than the bracket motion; therefore, the composite response is equal to the column response.

The composite frequency response for this system is illustrated in figure 22-12. This is the response curve that would be observed if the motor and bracket were tested while mounted on this column. Under these conditions there are two natural frequencies, namely, at 20 and at 50 cycles per second.

Most real machine structures are much more complicated than the above example; for instance, figure 22-13, taken from reference 15, shows the frequency response of a drill press. Logarithmic scales are used as graph axes in figure 22-13 to compress it to a reasonable size. The peaks in this figure represent resonances of the structure at 23, 33, 38, 70, 100, 110, 170, 230, 300, 380 and 500 cycles per second. Each peak is associated with a different vibration pattern of the various components that make up the drill press. Although the frequency response of most machine tools is more like figure 22-13 than the system response described by figure 22-12, vibration problems are generally not this complex because they often involve only one frequency. Consequently, the other resonances can be ignored

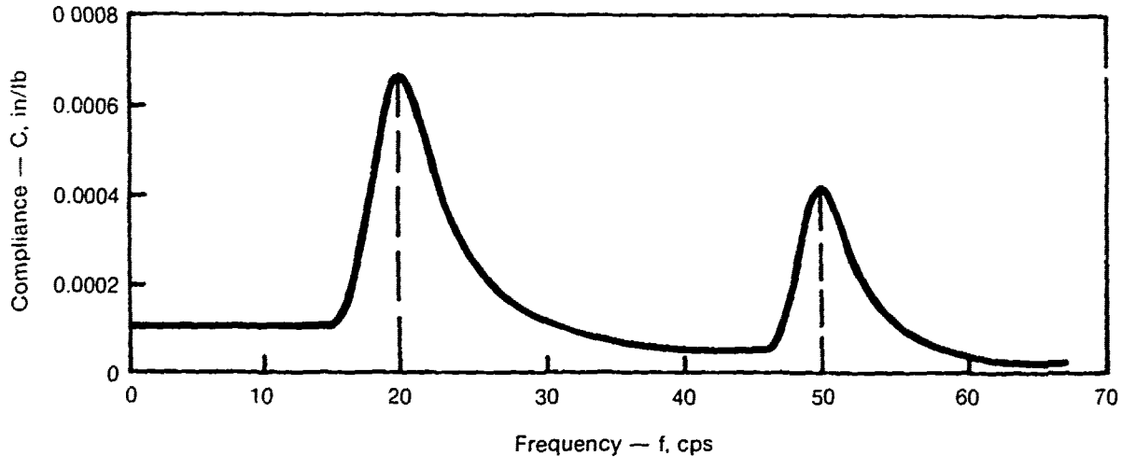


Figure 22–12 Composite frequency response of a mounted motor and column.

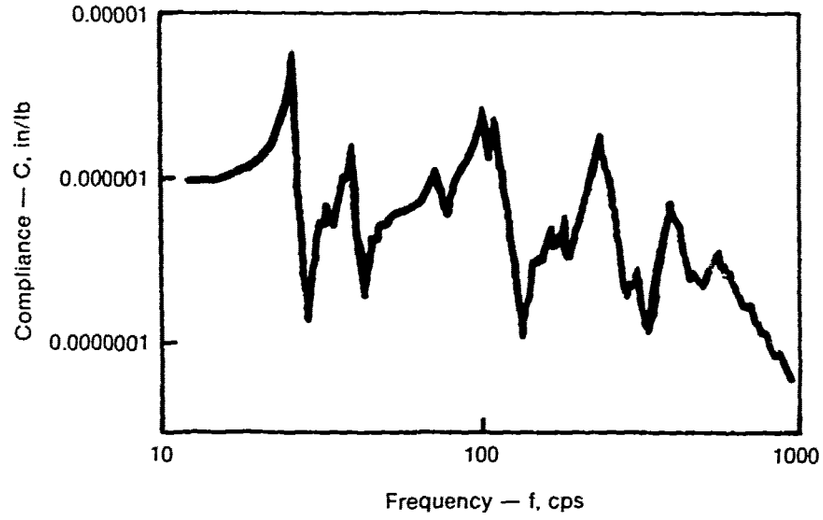


Figure 22–13 Frequency response diagram of a drill press.

and the real machine considered as a complex system with only one natural frequency.

Influence of Damping

It was noted that damping has a strong influence on the amplitude of free vibration when a system is started vibrating and allowed to die out. Damping also has a very strong influence on the amplitude of forced vibration, particularly at resonance. The family of curves in figure 22–14 shows the frequency response of a simple vibrating system with varying amounts of damping. In this figure the amplitude of the force is F, the vibration amplitude is A, and the frequency is f.

The degree to which a vibrating system is damped can be measured by its "resonance amplification" which is the vibration amplitude at resonance divided by the vibration amplitude at low frequencies for equal force amplitudes. The resonance amplification is also the ratio of the static stiffness, K, to the dynamic stiffness, K_d, at resonance. In figure 22–15 the static compliance is 0.00001 inches per pound while the maximum compliance at resonance is 0.00005 inches per pound. Therefore, the resonance amplification is (0.00005 ÷ 0.00001 =) 5.

For a lightly damped system the resonance amplification might be ten to thirty, while for heavy damping it might be one-and-one-half to four. These ranges point out the importance of damping in machinery. It is sometimes fairly easy to reduce the vibration amplitude by adding damping to a lightly damped structure vibrating near resonance. Almost any damping added to a lightly damped structure improves dynamic stiffness by a factor of two or three which, in turn,

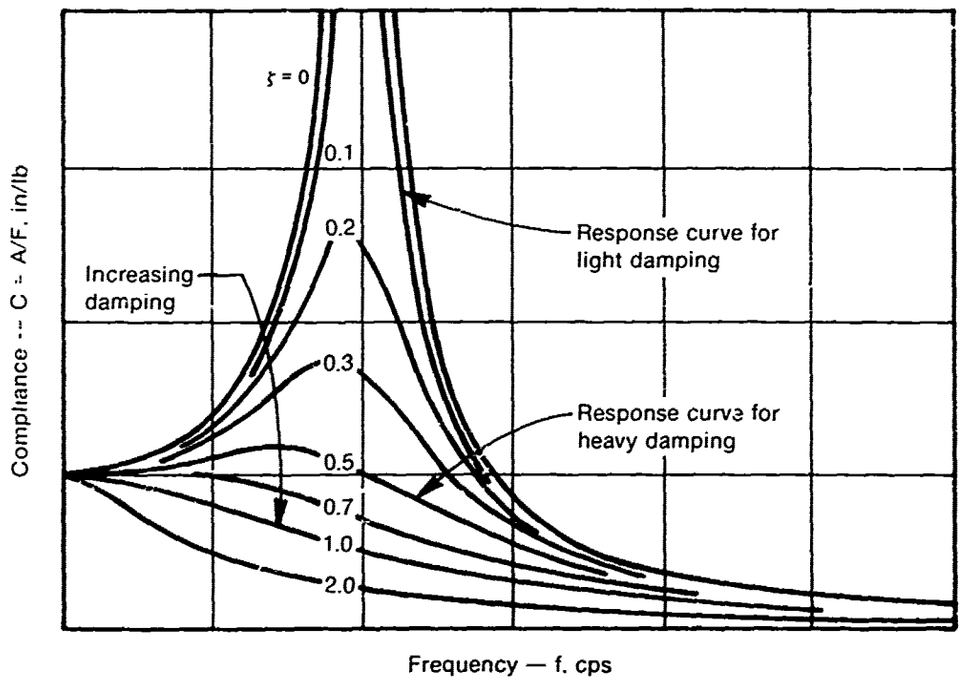


Figure 22–14 Influence of damping on the frequency response of a vibrating system.

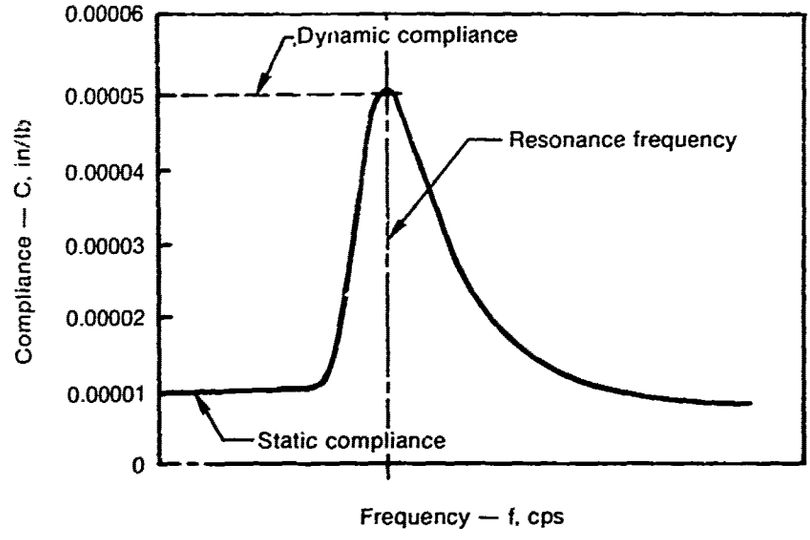


Figure 22–15 Determination of resonance amplification.

reduces vibration amplitudes by one-half to one-third of their original value. The same reduction in vibration amplitude can be obtained by increasing the static stiffness, K, (that is, decreasing the static compliance) which may be both difficult and expensive.

Data From Machine Structures

Figure 22-16 presents typical values of major natural frequencies on 13 different machine tools.[6-10] The 40 natural frequencies from these machines were combined into groups. Three natural frequencies were observed between

0 and 25 cycles per second, seven between 25 and 50 cycles per second, eight between 50 and 75 cycles per second; etc. The data of figure 22-16 show that natural frequencies often occur in the range of 0 to 100 cycles per second, that a fair number are widely spread over the range of 100 to 300 cycles per second, and that there were no important natural frequencies over 300 cycles per second for this particular group of machine tools

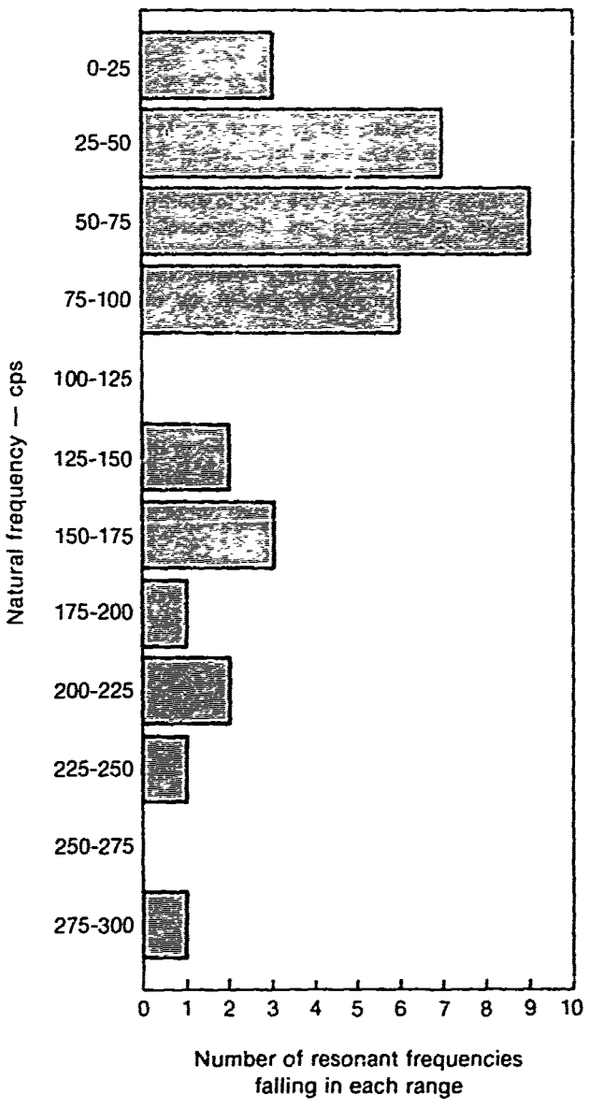


Figure 22-16 Typical values of natural frequencies on thirteen machine tools. (Compiled from Long,[6] Koenigsberger,[7] Ganoissart,[8] Tobias,[9] and Tlusty[10])

Low natural frequencies are typical of the vibration of heavy components, such as a whole machine rocking on its mounts. The 100 to 300 cycles per second range corresponds to vibrations of good, stiff, lower weight components, for example, a lathe bed. In practice, vibration problems occasionally occur at natural frequencies well above 300 cycles per second but, in most cases, these are associated with tool, not machine, vibration. Equation 22-4 demonstrates the characteristics necessary to obtain high natural frequency values. If a component has a stiffness of 500,000 pounds per inch, then its effective weight can be only about 19.5 pounds to give a natural frequency as high as 500 cycles per second, since:

$$f_n = \frac{9.8}{\pi}\sqrt{\frac{500{,}000}{19.5}} = 500 \text{ cps}$$

Any weight greater than 19.5 pounds will result in a frequency lower than 500 cycles per second. Boring bars and slender end mills are typical components with natural frequencies in the range of 500 cycles per second and above.

Another useful number is the resonance amplification, that is, the ratio of static to dynamic stiffness. Figure 22-17 shows this quantity for seven different machine tools.[6,7,9] These values normally fall in the range of 5 to 30. Lower values are obtained when the vibration involves sliding joints, such as the rocking of a lathe saddle on its ways. Higher values correspond to the vibration of solid components such as the twisting of a milling machine column.

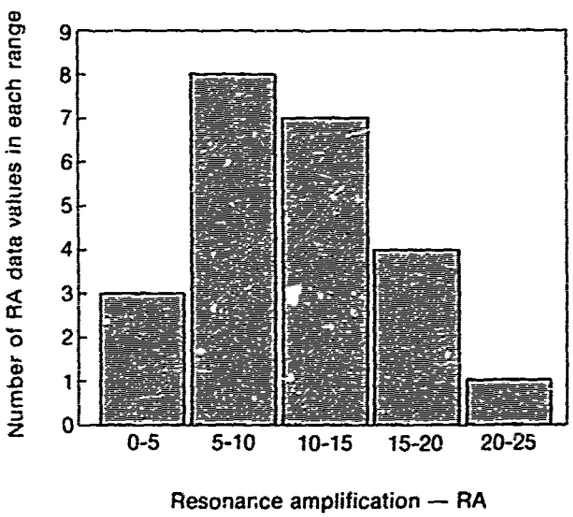


Figure 22-17 Resonance amplification data from seven machine tools. (Compiled from Long,[6] Koenigsberger,[7] and Tobias[9])

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The final value needed from the testing of real machines is the dynamic stiffness at resonance. Listed in table 22-2 are values obtained from nine machine tools of all sizes and shapes.

TABLE 22-2 Dynamic Stiffness at Resonance

MACHINE	DYNAMIC STIFFNESS, lb/in
A	15,400
B	27,500
C	33,300
D	33,500
E	58,900
F	71,500
G	122,000
H	410,000
I	478,000

Source: Data compiled from Long,[1] Koenigsberger, Gandissart,[2] Tobias,[3] and Tlusty.

A dynamic stiffness of 15,000 pounds per inch represents a light duty machine tool, not meant for heavy stock removal. Stiffness values of 400,000 and up represent machines that are capable of very heavy stock removal. Productivity of heavier duty machine tools will often be limited by the rigidity of the tooling, workpiece, or fixtures put on them.

SELF-EXCITED CHATTER

The vibrations discussed to this point were caused by forces resulting from factors including unbalance, eccentricity, and misalignments. There is, however, a totally different type of vibration known as self-excited chatter. When there is no external forcing, the structure itself determines whether there will be self-excited chatter, based on its rigidity and the cutting conditions. There are two types of self-excited chatter, high frequency chatter and regenerative chatter.

High Frequency Chatter

High frequency chatter is the result of high frequency vibration that sometimes occurs when tools become very dull. The tool vibrates in the direction of the cutting speed and results in high-pitched noise and a workpiece surface that is not deeply scalloped. This type of chatter is caused by the decrease in the rubbing force on the tool flank as the cutting speed increases. During cutting, a hard spot in the work, or a small vibration from a very small unbalanced force, may result in a very slight increase in cutting force. This, in turn, causes a very slight increase in the deflection of the cutting tool in the direction of the cutting speed. While the tool is deflecting in this direction, the speed is decreased slightly, causing a slight increase in cutting force, which causes more deflection, etc. This cycle continues until the cutting force has built up so high that the tool snaps back to its original position, overshoots, and the cycle repeats itself. This is not an important type of self-excited chatter and can always be solved by resharpening the tool. It is described here only to keep it from being confused with other types of machine tool vibration.

Regenerative Chatter

The important type of self-excited chatter is regenerative chatter. Regenerative chatter is difficult to troubleshoot since it is almost impossible to predict why the machine is chattering. Nearly every machining variable affects it sometimes, but only a few affect it all the time. This is the source of much of the shop lore about chatter, some of which is usually true and some of which is seldom true.

In regenerative chatter, a small disturbance, as a result of small forced vibrations, cutting force fluctuations, etc., causes the tool to vibrate relative to the workpiece. Small bumps are left on the machined surface. Since most turning cuts normally overlap the previous cut to some degree, these bumps make the cut a little deeper when they show up on the next revolution and have the same effect as a vibratory force. This causes the tool to vibrate even though the original disturbance has disappeared. For a well-behaved cut, the bumps left by the forced vibration on the second revolution will be a little smaller than the original bumps, and after a number of revolutions, they will totally disappear.

In a situation leading to chatter, the bumps will become greater each revolution and eventually become so great that visible, audible chatter occurs. The mathematical study of whether these bumps will grow or die out is called stability theory. This study is described in several different ways in some excellent technical publications.[8-12] The most important practical findings of stability theory are as follows:

1. In some ranges of machine speed, the tendency to chatter increases or decreases as the speed is changed slightly. This is because severe chatter can only occur when the wave that is feeding back from the previous revolution is in a certain relationship to the present motion of the tool. For example, if the bump in the workpiece surface is increasing the force, and at the same time the tool is moving out of the work decreasing the force, the net result might be zero force variation, and no tendency to chatter. This phenomenon relates to the cutting speed and the natural frequency of the machine. As speed is changed, the machine might go from heavy chatter to no chatter and back again to heavy chatter.

2. The chatter frequency is very close to that machine natural frequency having the highest resonance peak (lowest dynamic stiffness).

3. Chatter never occurs until the severity of the cut reaches a certain level, dependent on the minimum dynamic stiffness of the machine structure at resonance. Above a certain level of cut severity, chatter always occurs. The threshold level depends on many different cutting and structural parameters and is very difficult to predict accurately.

4. The maximum severity of cut which can be taken without chatter is closely related to the value of the min-

imum dynamic stiffness at the highest resonance peak. The frequency response that is most important is not the response of the machine but the response to the forcing between the tool and the workpiece, which includes the tool, tool holder, machine, fixturing, and workpiece. Doubling the least dynamic stiffness permits taking a cut that is approximately twice as heavy.

5. The tendency to chatter increases in proportion to the total length cutting edge engaged in the cut. The total cutting force and power are not important. How large a chip is being produced is not important.

6. The tendency of various workpiece materials to chatter is in proportion to the cutting forces they produce. Materials which produce high cutting forces are capable of only light chatter-free cuts. Materials producing low machining forces are capable of heavy cuts without chatter.

Chatter occurs when the cutting severity is equal to or greater than the structural vibration resistance. Mathematically, chatter occurs if:

$$QL_c \geq CK_{dm} \qquad \text{(Eq. 22-5)}$$

where:

- Q = workpiece material tendency to chatter
- L_c = total length of cutting edge engaged
- C = factor depending on cutting speed and resonant frequency
- K_{dm} = minimum dynamic stiffness at the highest resonance peak of the machine tool-workpiece system

Table 22-3 contains a compilation of Q values for a wide range of workpiece materials and hardness ranges.

TABLE 22-3 Chatter Tendency for Common Work Materials

MATERIAL GROUP	HARDNESS Bhn or R_c	CHATTER TENDENCY Q
Free machining carbon steels, wrought	100-150	0 9
	150-200	1.0
	200-275	1.2
	275-325	1.4
	325-375	1.6
	375-425	1.8
Carbon steels, wrought and cast	85-125	0.8
	125-175	1.0
	175-225	1.2
	225-275	1.4
	275-325	1.6
	325-375	1.8
	375-425	2.0
Free machining alloy steels, wrought	150-200	1.1
	200-275	1.4
	275-325	1.6
	325-375	1.8
	375-425	2.0
	45- 48 R_c	2.2
	48- 52 R_c	2.5
Alloy steels, wrought and cast; High strength steels, wrought; and Maraging steels, wrought	125-175	1.1
	175-225	1.3
	225-275	1.5
	275-325	1.7
	325-375	1.9
	375-425	2.1
	45- 48 R_c	2.4
	48- 52 R_c	2.9
Tool steels, wrought and cast	150-200	1.3
	200-275	1.6
	275-325	1.8
	325-375	2.0
	375-425	2.2
	45- 48 R_c	2.7
	48- 52 R_c	3.2

TABLE 22-3—Continued

MATERIAL GROUP		HARDNESS Bhn or R	CHATTER TENDENCY Q
Nitriding steels, wrought		200-250	1.4
		300-350	1.8
Armor plate		200-250	1.6
		250-300	1.8
		300-350	2.0
		350-400	2.3
		400-450	2.6
Structural steels, wrought		100-150	1.0
		150-200	1.2
		200-250	1.4
		300-350	1.6
		350-400	1.8
		400-450	2.0
Free machining stainless steels, wrought	austenitic	135-185	1.5
		185-225	1.7
		225-275	1.9
		275-325	2.1
		325-375	2.3
	ferritic & martensitic	135-185	1.5
		185-225	1.7
		225-275	1.9
		275-325	2.3
		375-425	2.7
Stainless steels, wrought and cast	austenitic	135-185	1.8
		185-225	1.9
		225-275	2.1
		275-325	2.3
		325-375	2.6
	ferritic & martensitic	135-185	1.8
		185-225	1.9
		225-275	2.1
		275-325	2.3
		325-375	2.6
		375-425	2.9
		42- 45 R_c	3.2
		45- 48 R_c	3.4
		48- 52 R_c	4.0
Precipitation hardening stainless steels, wrought and cast		150-200	2.4
		275-325	2.7
		325-375	3.0
		375-440	3.4
Gray cast iron		120-150	0.6
		150-200	0.8
		200-220	1.0
		220-260	1.2
Ductile cast iron		140-190	0.9
		190-225	1.1
		225-260	1.3
		260-300	1.5

TABLE 22–3—Continued

MATERIAL GROUP	HARDNESS Bhn or R_c	CHATTER TENDENCY Q
Malleable cast iron	110-160	0.9
	160-200	1.1
	200-240	1.3
	240-280	1.5
	280-320	1.7
Aluminum alloys, wrought and cast	30- 80	0.5
	80-125 (500 kg load)	0.6
Magnesium alloys, wrought and cast	50- 90 (500 kg load)	0.4
Titanium alloys, wrought and cast	150-200	1.2
	200-250	1.4
	250-300	1.6
	300-350	1.8
	350-400	2.0
	400-450	2.2
Copper alloys, wrought	10- 60 R_B	0.6-0.9
	60-100 R_B	1.0-1.2
Copper alloys, cast	40-100	0.6-0.8
	100-200 (500 kg load)	0.8-1.6
Nickel alloys, wrought and cast	80-150	1.5
	150-200	2.2
	200-250	2.8
	300-320	3.5
High temperature alloys	200-300	2.0-3.0
	300-375	2.0-5.0
	375-425	3.0-6.0
Refractory alloys, wrought, cast, and P/M	175-250	2.0-6.0
	250-300	3.0-7.0
	300-350	4.0-7.0
Zinc alloys, cast	80-100	0.5
Lead alloys Tin alloys	5- 30 (500 kg load)	0.3

22 MACHINE CHATTER AND VIBRATION

Machining Tests

A number of researchers have made cutting tests to study self-excited chatter. Figure 22-18 shows what happens during the turning of a bar if the depth of cut is gradually increased. The vibration amplitude is measured and plotted as a function of the depth of cut. The low vibration level at light cuts represents the background vibration level of the machine resulting from unbalance and irregularities in the drive train. The sharp increase in vibration at a certain "critical width of cut" is characteristic of regenerative chatter. The actual amplitude during chatter is likely to vary greatly. Not much is known about how the amplitude is determined, but once chatter occurs, the amplitude is almost always too great. The solution is to eliminate chatter rather than to determine why the machine vibrates at a certain level.

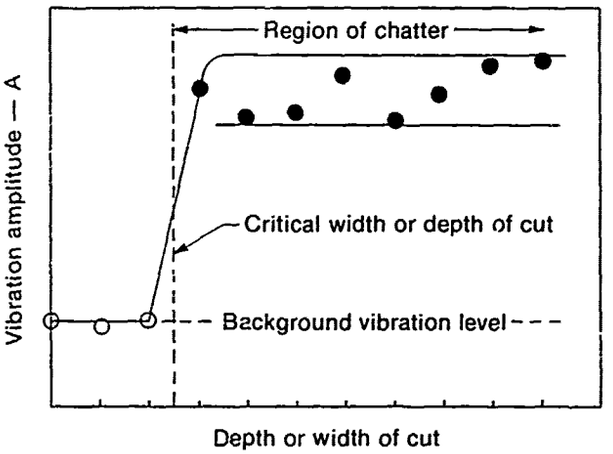


Figure 22-18 Experimental procedure to determine the critical width of cut for regenerative chatter.

Repeating this experiment at various cutting speeds demonstrates how this "critical width" is affected. Tests were run at the speeds and widths of cut denoted by the circles in figure 22-19. The solid circles represent chatter, the open circles represent chatter-free cutting, and the half-solid circles represent borderline chatter (more than background vibration but less than violent chatter). The dashed line is an attempt to sketch the borderline of chatter. Useful concepts to be learned from this figure include the following:

1. Below a certain width of cut, there is no chatter at any speed.
2. At slightly greater widths of cut, it is possible to get into or out of chatter by changing workpiece speed.
3. Chatter occurs at large widths of cut except at very low speeds.
4. Very large chatter-free widths of cut can be taken only if the cutting speed is low enough.

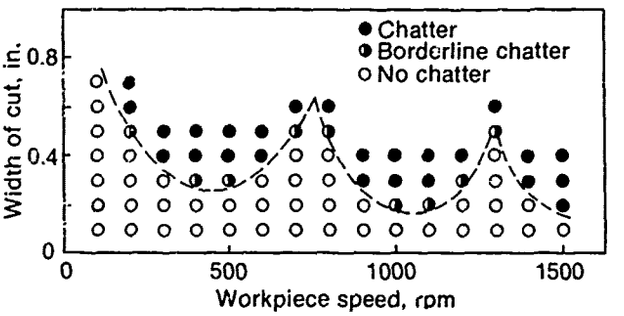


Figure 22-19 Experimental results of a study on regenerative chatter. Lobed line denotes borderline of chatter.

The reason for the "lobes" in the figure where certain speeds enable increased chatter-free widths of cut is the interrelationship between cutting speed and regenerative chatter. The lack of chatter at very low cutting speeds is called "low-speed stability." This phenomenon is not completely understood, but it is likely the result of small areas of tool-workpiece contact just behind the cutting edge. Experiments have been performed to show that dull tools and low tool flank clearance angles increase low-speed stability.

While chatter theory is very good at explaining experimental results (other than the enhanced stability at low cutting speeds), it is difficult to use in solving chatter problems. Chatter theory is not good at predicting just when a machine will start to chatter. More theory development is necessary before this can be done.

Factors Influencing Chatter

It seems logical that the more power consumed in a cut, and the higher the cutting forces, the greater the likelihood of chatter. This is wrong. Chatter theory says that the severity of the cut is the chatter tendency of the material multiplied by the length of tool edge in the cut. This relationship was given as equation 22-5. More power may or may not mean greater tendency to chatter. The chatter tendency of a workpiece material is closely related to the cutting forces and power that occur. The theoretical chatter tendency of a variety of workpiece materials is listed in table 22-3. The tendency to chatter is generally proportional to the expected cutting power. Low values are associated with aluminum, intermediate values with ordinary cast irons and steels, and high values with the difficult-to-machine alloys often found in aerospace applications. The chatter tendency numbers in the table show that, all other factors being equal, a cut three times as heavy can be taken with a 175 Bhn free machining carbon steel as with a 350 Bhn cast precipitation hardening stainless steel.

Another major factor influencing cutting severity is the length of the cutting edge. In rough turning, the length of the cutting edge in the workpiece is approximately equal to the radial depth of cut. Thus, if one-half inch is being taken off the diameter of a bar, the cut is twice as severe as if one-quarter inch were being removed. Note the lack of impor-

tance of the feed rate. According to chatter theory and supporting test data, light feeds are just as likely to cause chatter as heavy feeds. This implies that a radial depth of cut of 0.300 inch with a feed per revolution of 0.001 inch chatters sooner than a 0.250-inch radial depth of cut with a feed per revolution of 0.030 inch. While the heavier cut requires much more power, chatter is less likely to occur.

The important dimension affecting chatter in plunge cutting with a cutoff or form tool is the width of the tool. When cutting off a flimsy workpiece, a 1/8-inch wide cutoff tool is twice as likely to chatter as is a 1/16-inch wide tool. Again, the feed rate is an unimportant variable from the viewpoint of chatter. In drilling, the length of the cutting edges engaged is approximately equal to the drill diameter. The chisel edge has a strong stabilizing influence not predicted by theory. When a hole is enlarged and the chisel edge is not cutting, the tendency to chatter is proportional to the difference between the diameters.

Chatter in milling is a more complicated process to understand because its characteristics are three-dimensional. However, it can be simplified by the following procedure. The length of cut of a single tooth is first identified as illustrated in figure 22-20. The number of teeth in contact is then determined using the method shown in figure 22-21. The cutter should be "rotated" to produce the maximum number of teeth in contact, namely, the situation when one tooth (for example, tooth 1) is about to leave the cut. The total length of cutting edge in contact is the length per tooth times the number of teeth in contact. This number determines the cut severity. As in turning, feed rate is not considered since the chatter tendency in face milling is independent of the table feed rate. Consequently, for the same metal removal rate, a shallow cut at high feeds is preferable to a deep cut at light feeds.

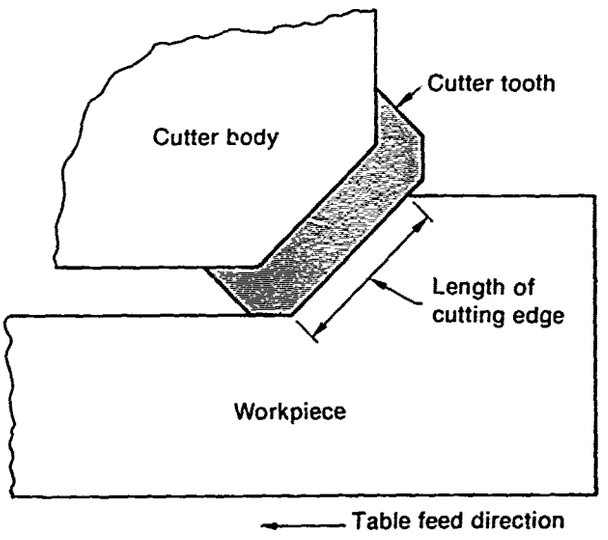
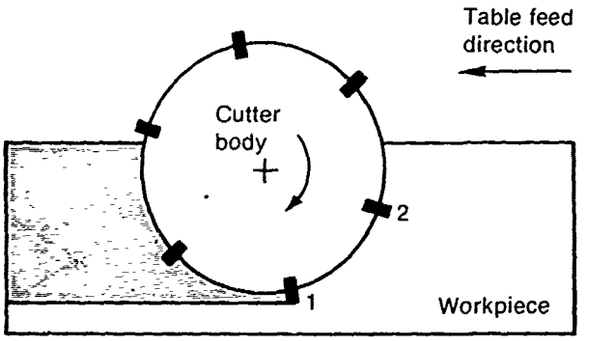


Figure 22-20 Schematic diagram showing length of cutting edge in milling.



Number of teeth in contact, N = 2

Figure 22-21 Schematic diagram illustrating the method that can be used to determine the number of teeth in contact with the workpiece during milling.

TROUBLESHOOTING CHATTER

Problem Identification

There are two types of vibration in machine tools: forced and self-excited. Multi-tooth cutter impact, gear drive irregularities and unbalance, and motion of the machine foundation contribute to forced vibration which results in surface irregularities in machined parts. In cutting operations free from these factors, vibration enters as self-excited chatter, a basic instability of the cutting mechanism itself. Figure 22-22 contains a flow chart that may be used to identify which type of vibration problem is present. The following discussion amplifies the steps in this process and provides guidelines relative to dealing with both types of vibration.

The vast majority of chatter problems are caused by self-excited vibration. A less frequent problem is chatter resulting from interrupted cuts forcing the structure at its resonant frequency. To solve these problems, the first step is to be able to distinguish between the two. Alternative fixes can then be logically accomplished.

The key to troubleshooting chatter problems is determining the chatter frequency. While special sensors and electronic instruments can be used, it is often possible to determine frequency without instruments by measuring the spacing between chatter marks on the workpiece surface. Figure 22-23 shows chatter marks on a typical turned surface. In the enlargement, the marks are numbered for easy reference. The correct measurement of chatter "wave length" is between corresponding points of mark 1 and mark 2, or of mark 3 and mark 4, or of mark 5 and mark 6. Note that the spiral, marks 1-3-5-7, has no significance, since the tool path is to be followed in making measurements. The tool makes mark 1, mark 2, etc., as it moves along the feed lines. After a complete revolution of the workpiece, it passes adjacent to mark 1 making mark 3, followed by mark 4, and another revolution later with marks 5 and 6, etc.

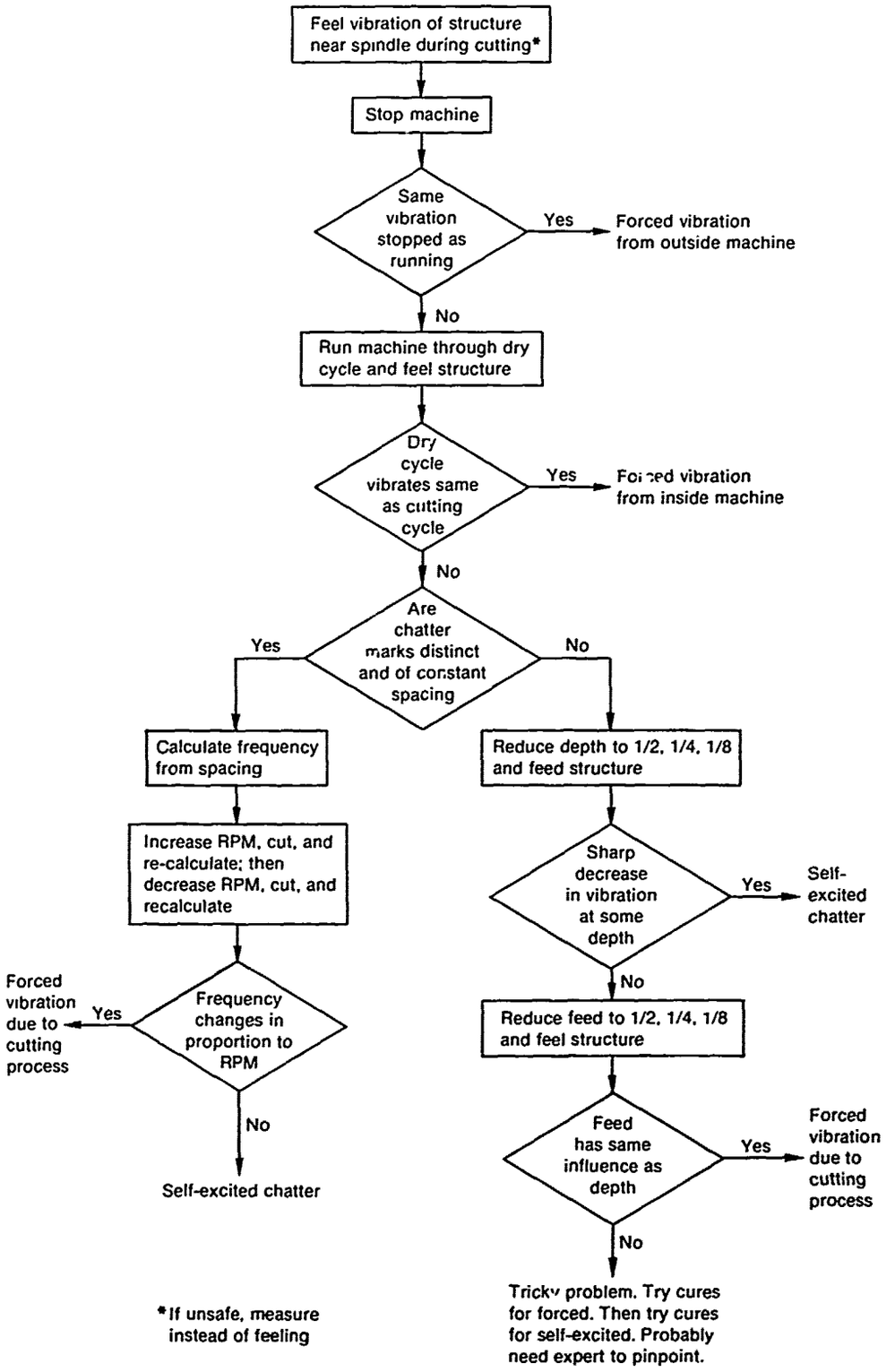
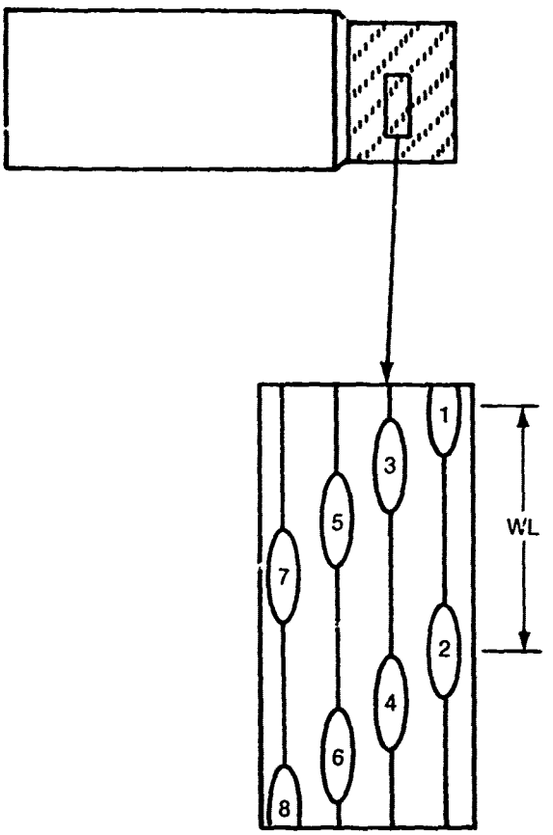
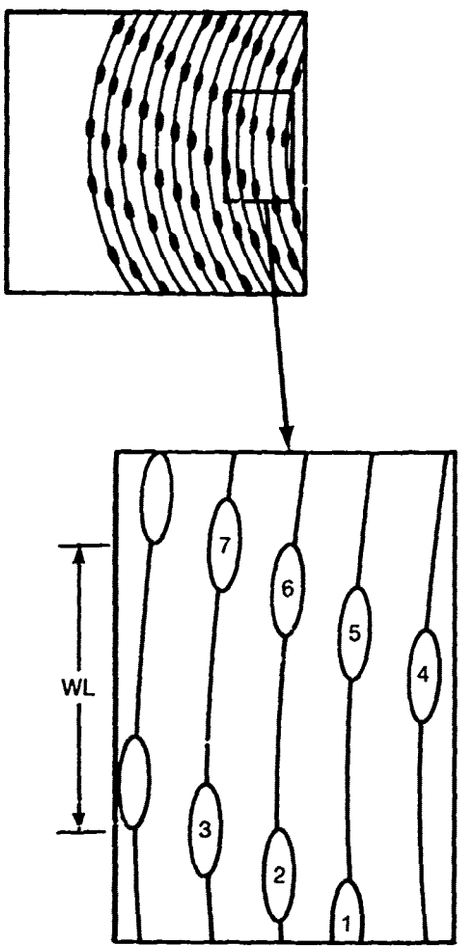


Figure 22-27 Flow chart for identifying vibration problems.



WL = Chatter wave length

Figure 22-23 Chatter marks on a turned surface.



WL = Chatter wave length

Figure 22-24 Chatter marks on a milled surface.

Figure 22-24 shows a similar situation for face milling. Again, no importance should be given to the spiral patterns, marks 1-2-3, or marks 4-5-6. By following the feed lines, the marks were found to be made in the following sequence:

Tooth 1: Mark 4; off the workpiece.
Tooth 2: Mark 5; mark 1; off the workpiece.
Tooth 3: Mark 6; mark 2; off the workpiece.

The chatter wave length is again measured by moving along, not across, feed lines.

In practice, the chatter wave length should be measured several times. Unequal measurements are usually caused by continuing vibration during the disengagment of the tool from the work. These extra vibration marks overlay the true pattern and make the spacing of marks meaningless. This problem can be minimized or avoided by disengaging the feed as quickly as possible or by rapid traversing away from the workpiece in the direction perpendicular to the chatter-marked surface.

Once the chatter wave length or spacing is measured, the frequency of vibration may be calculated as follows:

$$f = \frac{V}{5\,(WL)} \qquad \text{(Eq. 22-6)}$$

where:

f = vibration frequency in cycles per second
V = cutting speed in feet per minute
WL = length (or chatter mark spacing) in inches
5 = constant introduced because of the units used

For example, if the chatter wave length spacing in the previous milling example is 0.1 inch, and if the cutting speed is 200 feet per minute, then the chatter frequency is:

$$f = \frac{200}{5\,(0.1)} = 400 \text{ cps}$$

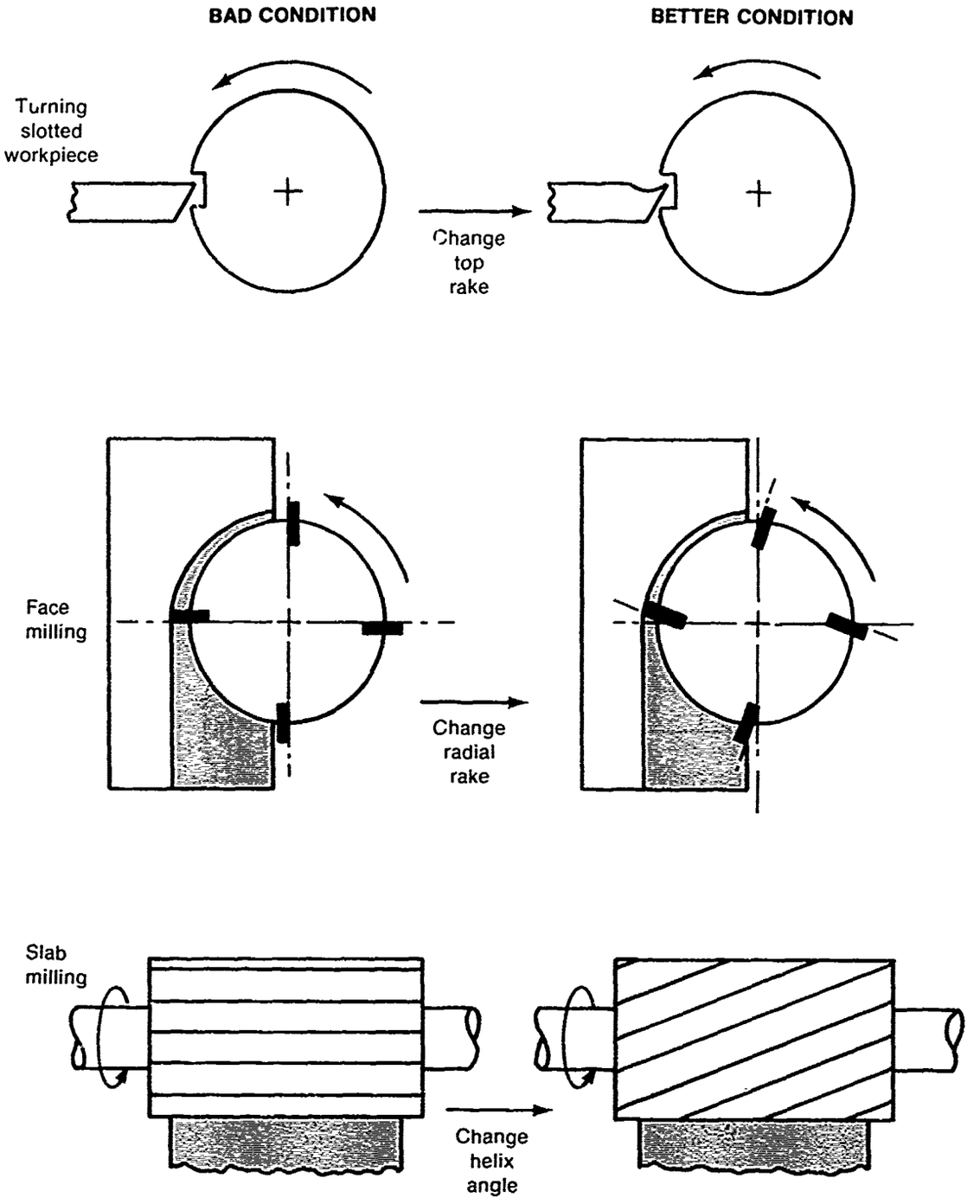


Figure 22–25 Suggested methods for reducing the magnitude of forced vibrations.

Whether the vibration problem is the result of interrupted cutting can be determined quickly by increasing or decreasing the cutting speed by 50 percent. After each cut at a different speed, measure the chatter marks and recalculate the frequency. The chatter is the result of interrupted cutting if the frequency changes in proportion to the cutting speed. The fundamental principle here is that self-excited chatter occurs at a frequency near the natural frequency, regardless of the spindle speed, but forced vibrations always occur at the forcing frequency. A 50-percent change in cutting speed will make very little change in the frequency of self-excited chatter. The same change in speed

should change the frequency of forced vibration by 50 percent.

Another sure way to identify self-excited chatter is to reduce the severity of the cut. As the length of cutting edge engaged is decreased, a point is reached where a small decrease in cutting edge length causes a dramatic decrease in vibration. The decrease may be associated with "width of cut" or "depth of cut" depending on the particular cutting operation; however, it is never associated with the feed rate.

Elimination of Forced Vibration

If the problem is identified as being forced vibration, try either to reduce the magnitude of the forcing vibration or to increase the stiffness of the machine tool system. One way to reduce the magnitude of the forced vibration is to change tool angles so that the cutting load is picked up gradually. Figure 22-25 illustrates how bad situations can be changed into better ones. Another possible way to reduce the forced vibration is to reduce the feed rate. The vibration amplitude should change in proportion to the feed rate; therefore, if only a slight reduction is needed, decreasing the feed rate is an appropriate solution.

A change in the cutting speed often has dramatic effects on reducing forced vibration. Either an increase or a decrease in cutting speed, depending on which side of the resonance peak the machine is operating, may reduce the vibration enough to solve the problem. If the machine tool is being forced at a frequency just below the natural frequency, a small increase in speed will increase vibration amplitude, and further increases in speed will reduce vibration amplitude. On the other hand, a reduction in speed will immediately reduce amplitude. The opposite response is true if the forced vibration started out above the natural frequency. Since there is no way to tell in advance which situation applies, try either an increase or a decrease in cutting speed of at least 20 percent, whichever is easiest. If the results are not positive, try changing the speed in the other direction.

A technique that sometimes works in milling is to change the direction of the cutting force away from a weak direction of the structure toward a strong direction. This cannot always be done scientifically because force direction or machine directional rigidity may not be known. Changes such as feeding a face mill in the Y-direction rather than in the X-direction or changing the table feed direction in slab milling have been known to work.

Elimination of Self-Excited Vibration

Decreasing the length of the cutting edge in the cut will eventually eliminate self-excited chatter. In turning, this means reducing the radial depth of cut. In face milling, the axial depth can be reduced or every other tooth can be removed from the cutter with a corresponding reduction in feed rate. In cutting with an end mill, either the radial depth or the axial depth may be reduced, or a cutter with fewer teeth may be used.

Dulling or stoning the cutting edge is a method that often reduces regenerative self-excited chatter, particularly at low cutting speeds. Increasing the feed rate is another helpful method of reducing self-excited chatter. Self-excited chatter occurs less frequently for a heavier chip load of 0.010 inch or greater than for a light chip load of 0.005 inch or less. The heavier feed rate increases the cutting force but not the length of cutting edge engaged in the workpiece and, hence, slightly reduces the tendency of the material to chatter.

If the cutting speed is low (less than 200 feet per minute) or if the chatter frequency is high (1,000 cycles per second or more), a reduction in the cutting speed tends to reduce chatter. Almost any size cut can be taken without chatter if the cutting speed is lowered sufficiently. This added stability at low speeds is associated with springback of the machined surface just behind the cutting edge. A small contact force is created that tends to push the tool out of the work and resist chatter. The effect is much more pronounced for tools with low clearance angles. Tool wear stabilizes the cut since the worn edge acts like a low clearance angle generating a force which opposes tool penetration into the work. If the clearance angle and the speed can be reduced, chances of solving the problem are improved.

One final technique which applies to both self-excited and forced vibration is redirecting the cutting force toward a stiffer direction of the structure. For example, the turning tool with a 45-degree lead angle on the top in figure 22-26 will chatter much sooner than the one shown on the bottom with a zero lead angle. Because the cutting force is perpendicular to the cutting edge, a major portion of the force is aimed in the weak bending direction of the bar in the first case (a). However, in the second case (b) the force is aimed along the very rigid axis of the bar. There is no simple rule for aiming the force in a more rigid direction except in the simplest of cases. A combination of analysis and judgment is required.

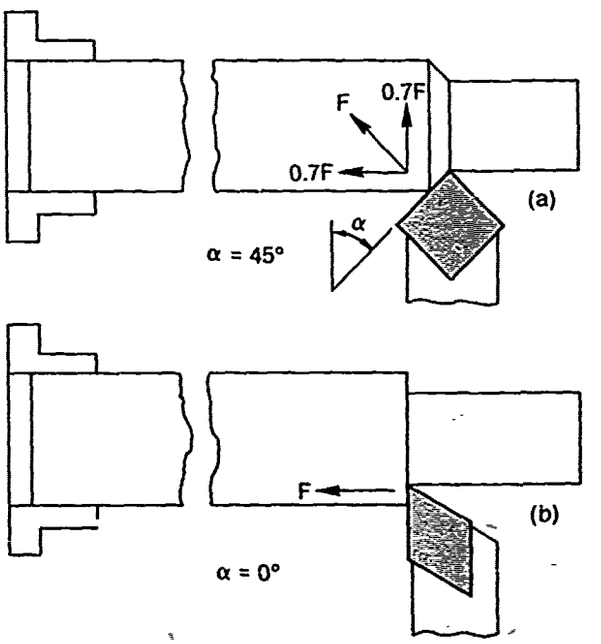


Figure 22-26 Influence of lead angle, α, on direction of cutting force, F.

22 MACHINE CHATTER AND VIBRATION

REGENERATIVE CHATTER CHECKLIST

By applying the principles outlined above, many difficult vibration and chatter problems can be solved. Others require experts who have powerful instruments to give them data not available from a simple approach. Often the measurements lead to the conclusion that the machine has a weakness that can be corrected. Further analysis leads to suggestions for stiffening the machine, or adding a vibration damper. Even if it is eventually necessary to go to an expert for a solution to a particular vibration problem, the suggestions contained in table 22-4 should always be tried first. There is a good chance that one of these simple techniques will yield a solution.

TABLE 22-4 Checklist of Methods To Eliminate Vibration and Chatter Problems

TURNING

- Lower the stock removal per pass.
- Try a heavier feed if presently feeding below 0.010 inch per rev.
- Reduce the width of cut of the form tool.
- Use a steadyrest on slender bars.
- Chuck slender bars at their center and turn end-for-end.
- Use a smaller nose radius on the tool to keep the cutting forces away from the radial direction.
- Modify the cutting edge angle to be more radial keeping the forces away from the radial direction.
- Consider using the Kennametal Roller Devibrator® (or equivalent) on slender bars.
- Minimize the tool overhang.

BORING

- Use the largest possible boring bar diameter.
- Reduce the boring bar length to as short as possible.
- Make the tool nose radius as small as possible to minimize the radial force.
- Use a side cutting edge angle as radial as possible to reduce the radial force.
- Reduce the stock removal in roughing.
- Consider a damped boring bar for L/D's greater than 6.
- Consider solid carbide boring bars for L/D's over 4.
- Consider reaming after semi-finish boring for finish boring problems.
- Consider multi-tooth boring bars for roughing operations.

MILLING

- Reduce the stock removal per pass.
- Reduce the width of cut.
- Try heavier feeds if presently feeding below 0.010 inch per tooth.
- Try reducing the RPM when using high speed steel cutters.
- Try dulling the cutting angles of high speed steel cutters.
- Avoid high wrap-around angles in end mill cutting.
- Generate an interior radius rather than plunging the cutter.
- Try using serrated edge end mills.
- Use a cutter with half as many teeth.
- Remove half of the inserts in a face milling cutter.
- Try a face mill with a random tooth space design.
- In face milling, use more of a corner angle to get cutting edge more toward the finished surface and reduce x and y horizontal force components.
- In face milling, try feeding at 90° to the present feed direction.
- Try an axial stepped milling cutter design.
- Try changing from climb to up milling (or vice versa) to change the force direction.

GRINDING

- Reduce the width of grind.
- Reduce the stock removal rate.
- Dress the grinding wheel more frequently.
- Use a sharper dress (more lead, greater depth, sharper diamond) if possible.
- Use a softer grinding wheel.
- Reduce excessively high work speeds.
- Use a backrest on slender workpieces.

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SECTION 23

NUMERICAL CONTROL MACHINING

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INTRODUCTION

Numerical control (NC) is a sophisticated and versatile form of automation that continues to significantly impact the manufacturing industry. One of the more commonly accepted definitions of NC is that given by the Electronics Industries Association (EIA): "A system in which motions are controlled by the direct insertion of numerical data at some point The system must automatically interpret at least some portion of this data."

The numerical control system consists of the five basic, interrelated components as follows:

1. Data input devices
2. Director (or machine control unit)
3. Machine tool or other controlled equipment
4. Servo-drives for each axis of motion
5. Feedback devices for each axis of motion

These components operate together to provide an integrated system that performs nearly all of the machine operator's functions. While there are many varieties of these components available, they all can be categorized into one of the five groups listed above. The major components of a typical NC machine tool system are shown in figure 23.1-1.

Numerically controlled machine tools are commonly classified as being either point-to-point or continuous path. The simplest form of numerical control is the point-to-point machine tool used for operations such as drilling, tapping, boring, punching, spot welding, or other operations which can be completed at a fixed coordinate position with respect to the workpiece. The tool does not contact the workpiece until the desired coordinate position has been reached; consequently, the exact path by which this position is reached is not important. The programming of these systems is elementary and can be done by anyone who has both the ability to read engineering drawings and a basic understanding of machining principles and practices.

With continuous path (that is, contouring) NC systems, there is contact between the workpiece and the tool as the relative movements are made. Continuous path NC systems are used primarily for milling and turning operations that can profile and sculpture workpieces. Other NC continuous path operations include: flame cutting, sawing, grinding, welding, and even operations such as the application of adhesives. We should note that continuous path systems can be programmed to perform point-to-point operations, although the reverse (while technically possible) is infrequently done. One important concept of continuous path operation is that the positional relationship between the tool and the workpiece must be provided for at all times because the path the cutter follows in moving from one position to another ultimately determines the workpiece shape.

SELECTION OF PARTS FOR NC MACHINING

NC is not the answer to all manufacturing problems. Conventional machine tools or automatic transfer-line machinery may provide better solutions to particular problems. Usually, the answer is based on lot size. NC is often advantageous for small or moderate lot sizes, for example, from 1 to 100. It is important to note that there is a predominance of lot sizes of this magnitude in industry today.

As manufacturing costs continue to rise, the economic necessity for cost-reduction programs and increased machine-tool utilization requires that careful consideration be given to the selection of numerical control applications. Since various philosophies exist among companies as to when NC should be used, there currently is no general rule that can be applied.

Parts selection for NC should be based on an economic evaluation, including scheduling and machine availability. Economic considerations affecting NC part selection include alternative methods, tooling, machine loadings, manual versus computer-assisted part programming, and other applicable factors.

Thus, numerical control should be used only where it is more economical or does the work better or faster, or where it is more accurate than other methods. The selec-

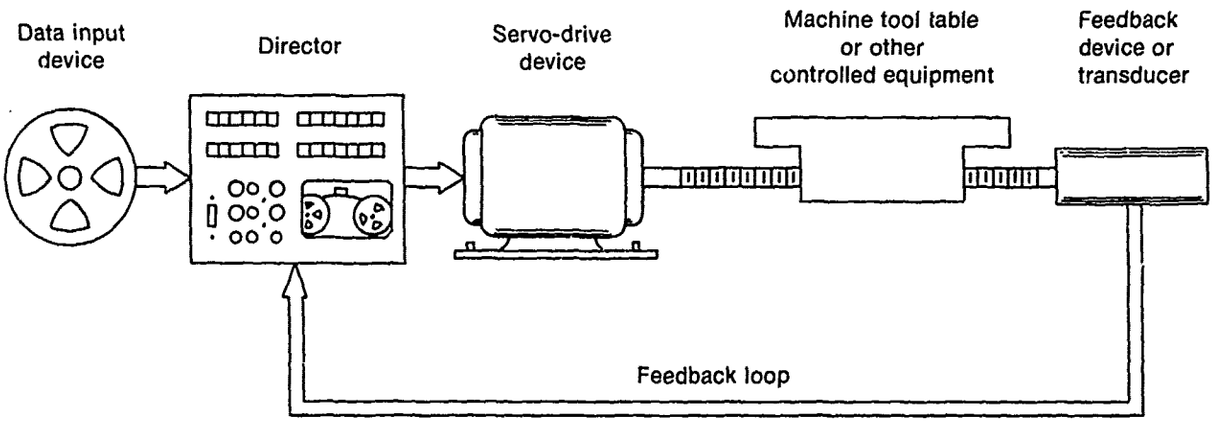


Figure 23.1-1 Simplified numerical control system.

23.1 NC Machining Guidelines

tion of parts to be assigned to NC has a significant effect on its payoff. The following guidelines which may be used for parts selection describe those parts for which NC may be applicable:

1. **Parts which require SUBSTANTIAL TOOLING COSTS in relation to the total manufacturing costs by conventional methods**

   For example, NC should be used where expensive drill jigs, templates, or models are otherwise required. Drill bushings are not needed for NC; consequently, the initial or replacement costs associated with drill jigs in conventional drilling do not apply to NC.

2. **Parts which require LENGTHY SETUP TIMES compared to the machine run time in conventional machining**

   Rapid setup of NC jobs is common because part fixturing is simple. This makes NC economical for jobs where the machine run time is short.

3. **Parts which are machined in SMALL OR VARIABLE LOTS**

   Usually, the savings in setup time and handling using NC machine tools outweighs the higher operating costs of NC compared to conventional equipment.

4. **A WIDE DIVERSITY OF PARTS requiring frequent changes of the machine setup and a large tooling inventory if conventionally machined**

   This is a common situation in the aerospace, the machine tool, and the job shop industries. The quantities are not large enough to justify transfer machines as used in the automotive industry. The part dimensions and configurations may cover such a broad range that adequate inventory may be prohibitively large. NC may be used to provide spare part capability without storing the parts or bulky fixtures and tooling after the product is no longer marketed.

5. **Parts which are PRODUCED AT INTERMITTENT TIMES because demand for them is cyclic**

   This occurs where part requirements are seasonal or subject to production scheduling for assembly. Whereas conventional machining requires the costly storage of templates, tools and fixtures, NC requires only tape storage.

6. **Parts which have COMPLEX CONFIGURATIONS requiring close tolerances and machined relationships**

   NC with multiaxis capability makes simultaneous machining motions possible, and parts can be produced which previously were impossible to produce by conventional methods.

7. **Parts which have MATHEMATICALLY DEFINED COMPLEX CONTOURS**

   In general, if a part surface can be defined mathematically, it can be machined by NC.

8. **Parts which require REPEATABILITY from part to part and lot to lot**

   Data stored on tape or other input media will not permit an operation to be forgotten or skipped.

9. **VERY EXPENSIVE parts where human error would be very costly and increasingly so as the part nears completion**

   Even prior to machining, the cost of the forging or casting required may be high or the material itself may be expensive.

10. **HIGH PRIORITY parts where lead time and flow time are serious considerations**

    Usually, the flow time from blueprint to the finish-machined part is considerably less with NC machining, provided that the programming can be expedited through any backlog. Special tooling, if required, is usually simpler for NC than for conventional machining and can be designed and built faster.

11. **Parts with ANTICIPATED DESIGN CHANGES**

    Changes can be made on the tape or other data input media with relative ease compared to changes in hard tooling.

12. **Parts which involve a LARGE NUMBER OF OPERATIONS or MACHINE SETUPS**

    Part operations may be complicated, tedious, and difficult to follow. NC machining allows data on the tape to be utilized repeatedly once it is satisfactorily programmed. This is a considerable advantage over conventional machining where the complexity of following the instructions continues for each part. NC can also utilize a variety of successive, interchangeable tools without time losses for machine stoppage, setups, and transfers. For example, parts requiring straight-cut milling combined with many drilling, reaming, and tapping operations are excellent choices for the less sophisticated machining centers.

13. **Parts where NONUNIFORM CUTTING CONDITIONS are required**

    The cutting speed, feed, or depth of cut may need to be varied because of the part configuration. Such variations may be incorporated into the NC program.

14. **Parts which require 100 percent INSPECTION or require measuring many checkpoints resulting in high inspection costs**

    With the inherent dimensional repeatability of NC, it is often necessary to inspect only the first and last pieces completely and to spot check the critical dimensions on the other pieces.

15. FAMILY OF PARTS

These are parts that are in the same general class with respect to configuration or manufacturing sequence but vary in dimensions. This situation is particularly common in the machine tool industry. Common setups may be used for these parts, and programming time may be reduced by using the same basic format or macro's for all the parts in the family.

16. MIRROR-IMAGE PARTS

In the aerospace industry, it is quite common to have dimensionally identical parts which are mirror images of each other. These are usually referred to as left- and right-hand parts. Many similar situations exist outside the aerospace industry. For example, a housing with internally and externally machined surfaces may be impossible to fabricate in one piece. For manufacturing purposes, it could be made in two symmetrical halves (that is, left- and right-hand parts). With NC, both parts may be made utilizing one program tape by actuating the mirror-image switch on the control and changing to opposite hand cutting tools if required. The mirror-image capability is provided as an option on most NC systems.

17. **NEW PARTS for which conventional tooling does not already exist**

Production of a new product alone is seldom sufficient justification for using NC. Significant cost savings do not begin to accrue until new parts are planned for NC. However, in the first stages of the NC installation, a proper selection balance should be maintained between old and new parts. In this manner, during the learning period the NC machine can be properly loaded while allowing conventional machining of the old parts should any problem arise. This dual planning eliminates needless part delays and possible stock outs.

18. **Parts which are suitable for MAXIMUM MACHINING on NC machine tools**

Although it is best if parts can be machined completely on NC machine tools, allied conventional machining operations often are required. An exception is the manufacturing cell or work center concept common to group technology. In this situation, the operator of an NC machine may also do part deburring, drilling or tapping of holes on peripheral equipment manually while waiting for the NC machine to finish its cycle. By balancing operations timewise between the NC machine and manual equipment, a reduction in the overall processing time can be achieved. Usually, however, if only the most time-consuming, conventional operations are replaced by NC, many of the benefits of NC will be minimized or eliminated.

Cost studies should be performed for parts that are selected when one or more of the above guidelines apply. Sometimes even simple configuration parts will show savings by NC production, so cost studies are advised for these parts as well. Various cutting conditions should be investigated and analyzed to determine the most economic operating conditions. Computer and calculator programs are available to carry out the simple, but long and tedious, calculations.[1,2] Machining data relating tool life with cutting speed and other parameters are required for these calculations. Such data are contained in this and in other MDC publications. Section 21 of this handbook and reference 3 at the end of this section outline and demonstrate this approach.

SELECTION OF MACHINING CONDITIONS FOR NC MACHINING

The importance of selecting proper machining conditions is an essential step in good machining practice. To be successful, every machining operation using NC equipment must be based on a sound foundation of planning, coordination and feedback. The most widely used criteria for machinability include tool life, surface roughness, accuracy, and power consumption. Of these, tool life is the most commonly used and has been extensively related to the cutting conditions. Machinability data are needed to predict the life of a cutting tool in relation to some known reference value. It is important to be aware of all the variables that may affect the resulting tool life whenever data are accumulated for future use. Some of the more important variables, in broad groupings, include the following:

- Cutting tool design including material
- Tool characteristics
- Workpiece properties
- Characteristics of the machine tool
- Dimensions of the cut
- Presence or absence of a cutting fluid and its properties

With a knowledge of these variables and the degree of variability within each grouping, it is possible to achieve predictable tool life.

Machinability data in various degrees of sophistication are available for use by industry for NC machining. These data include (1) recommended starting conditions and (2) wide range machining data.

This *Machining Data Handbook* contains recommended starting conditions for most of the significant work materials and machining operations. It supplies the recommended feed, speed, tool material, tool geometry, and cutting fluid, as well as data for determining the horsepower requirements for various machining operations. These recommended starting conditions are currently the most practical and readily accessible data for general shop application.

Detailed machining data covering the tool life obtained under a wide range of machining parameters, such as speed, feed, tool material, tool geometry, and cutting fluids, are very useful in selecting a set of conditions for machining at lower costs or higher production rates. Detailed machining

parameters can be obtained from laboratory studies or from shop studies by varying the pertinent parameters and observing their effect on tool life.

Machinability data that are accurate, reliable and appropriate are essential to the success of NC machining. The philosophy of NC manufacturing, involving its high level of automation, demands the use of the best available data. The high cost and productive capacity of NC are frequently such critical factors that every effort must be made to find the best set of operating conditions.

Since data for conventional machining are often conservative, they are not particularly suitable for NC machining operations. Further, such data are often too simple or based on information that is too generalized. NC machining conditions selected from these data may result in significant machine underutilization and reduced profits.

For NC machining, the feeds and speeds are most often computed quantities rather than being dependent solely on operator judgment. The effect of this is more consistent results because the operator-induced variables are minimized or eliminated. Another approach sometimes employed with NC feed and speed selection is to program the cutting conditions on the high side and then use override controls to suit actual conditions.

Specialized machinability data systems are being developed for NC because simple data systems are inadequate. Reasons for this inadequacy are as follows:

- The higher cost of NC machine tools and machining time
- Programming costs
- Variations in NC machine tools and NC production requirements
- The shift of responsibility for NC operations from operator to programmer

The computer has an integral role in both the development and the maintenance of specialized machinability data systems for NC. The number of variables, including materials, cutting tools, etc., suggests that for a system to be both practical and efficient, and at the same time accurate and realiable, use of the computer is essential. Also, in a computerized machinability system, data can be easily updated to incorporate the current conditions existing for a given operation.

Work is in progress in the United States and abroad to develop computerized machinability data systems. These systems vary in their final purpose and application, but many are being devised to faciltate both numerical control programming and machining. Some are being designed for numerical control as well as for conventional machining. They all have as a common purpose the systematic and rapid selection of data for the ultimate user.

TOOLING FOR NC MACHINING

NC machine tools provide more cutting time than conventional machines. Conventional machines may use some 30 percent of their total available time actually cutting, while for NC machines, cutting time may be on the order of 70 percent. A major contributing factor in this reduction of nonproductive time has been the development of quick-change and preset tooling. Because there is high initial investment in the capital equipment used, it is essential that every avenue be followed that increases the percentage of machining time. The primary objective of tooling for NC is to assure that there is complete compatibility between it and all the engineering and economic criteria by which numerically controlled machines are justified.

Tooling systems for NC must incorporate the principles of eliminating operator error and maximizing productivity. These goals can be achieved using the strategies that follow:

1. Automatic tool changing for sequential operations
2. Off-machine presetting of tools
3. Speeding up the manual replacement and changeover of tools
4. Reducing machine adjustments caused by tool deflection and wear
5. Using the NC program to facilitate tool selection and changing

For NC applications, it is typical that less hard tooling is required than for comparable operations on conventional machines. Numerical control, with its relatively inexpensive tooling, eliminates the need for expensive jigs, fixtures, cams, master parts, form tools, etc. Lower tooling costs enhance the justifiability of parts for production with NC equipment. The inherent accuracy and repeatability of parts produced using NC result in a need for less assembly tooling. It should be emphasized that while less tooling is required for NC machining, the tooling that is used must be more precise so that the inherent precision of the NC equipment can be fully utilized.

Because numerical control machining is flexible, it is important to select tooling that is simple in design so that it functions with a high degree of dependability. The tooling should be designed so that the cost of maintenance is low and components may be easily replaced or interchanged. Complex tool designs are more likely to cause machine downtime. While tool costs are a very small part of the finished product cost when things are going properly, improper tool design can cause excessive difficulty and high manufacturing costs. For some applications, there may be a need for heavy stock removal; for others, thin wall sections may have to be machined. If the tooling system is carefully designed, both applications can be handled with a single tool holder; only the geometry or grade of the insert need be changed.

NC machining has introduced a number of new concepts for the operation and organization of modern machine shops. One of the more important concepts has been the introduction of tool standardization. Tool standardization becomes increasingly important as the number of NC machines in a plant increases. Tool standardization means

finding the minimum number of types of tools, adapted to the NC system, that will do the majority of the jobs on as wide a variety of machines as possible.

The advantages of tool standardization can be signficant. With standardization, substantial reductions can be expected in the amounts of both initial and backup tooling. In addition, the inventory of tools can be maintained at a reasonable level, and the interchangeability of tooling among various machines can provide a decided intangible operational advantage. The specific method by which tools can be standardized obviously will vary. For single point tools, these methods might include control dimensions, insert styles and size, and tool holder style.

Tooling which can be quickly inserted into a machine tool spindle and easily locked in place with a minimum of effort and which will cut to a predetermined size without further adjustment while on the machine is referred to as quick-change, preset tooling. The term preset tooling applies to a wide variety of tooling from simple indexable-insert, single-point tools to coded, preset tool holders for use in automatic tool changers. Preset tooling is not a new idea; however, with the increasing use of NC machine tools, its application is rapidly growing. Because NC machines are costly to operate, the changeover time between jobs must be minimized. Preset tooling can sharply reduce this downtime.

The actual presetting of tools is not difficult, as there are mechanical and optical tool-setting devices readily available. Most commonly, the tools will be set in toolrooms; although, in some cases where machine operators have both the time and the ability, they may make up preset tools at the machine tool location. Presetting the tools in the toolroom is most desirable, especially when considering the potential costs of operator mistakes and machine downtime for trial cuts or interruptions to adjust tooling. Many shops maintain a file of tool-setting drawings used by both programmers and toolroom employees. These drawings describe the cutter, identify it by a tool number, and establish a setting length. With this approach, all parties can be confident that the job will be done correctly.

A number of numerical control machines have automatic tool-changing capabilities which further enhance the application and use of preset tooling. While the actual mechanism by which the tools are interchanged between the spindle and tool-changer magazine varies from machine to machine, it is important to note that the operation is both programmable and fast (on the order of a few seconds), which reduces nonproductive time. Preset tools for automatic tool-changer systems are either positioned in their numerical machining sequence or separately identified and coded to respond to specific tape commands.

Although most presetting of tools is done on equipment in an area away from the machine tool, there is a different arrangement on some NC machine tools that allows presetting the tools right on the machine. On these machines, control circuits are used which enable "zeroing" on each tool in relationship to the tape and the workpiece. The operator mounts a tool in the spindle and advances it to the workpiece until it contacts a feeler gage. While in contact with the feeler gage, tool length compensation controls are adjusted to establish a zero starting point for that tool. This procedure is repeated for each tool used on that job.

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A-Axis: An angle defining rotary motion around the X-axis such that positive *a* is in the direction to advance a right-handed screw in the +X direction.

Absolute Accuracy: Accuracy measured from a reference zero which must be specified.

Absolute Address: The actual address of a computer memory location, as contrasted to a relative address which may not be determined until it is used during the execution of an instruction.

Absolute Coordinate: The values of the X, Y, and Z coordinates with respect to the origin of the coordinate system.

Absolute Dimension: A dimension expressed with respect to the origin of a coordinate axis not necessarily coincident with the absolute zero point. Also called *Coordinate Dimension.*

Absolute Reference Point: An arbitrarily fixed zero location on the machine table from which part coordinates are dimensioned. For antithesis see *Floating Zero.*

Absolute System: A system in which all coordinate locations are measured from a fixed location on the machine table or from an absolute zero point. The zero point on some machines is established by the manufacturer at a fixed location, while on other machines it may be established by the NC programmer.

Absolute Zero Point: The point of absolute zero for all machine axes.

ACC: See *Adaptive Control Constrained.*

Acceptance Test: A test for evaluating the performance, capabilities and conformity of software or hardware to predefined specifications.

Accuracy: Conformity of an indicated value to the true value, that is, an actual or an accepted standard value (see *Precision* and *Reproducibility*). The accuracy of an NC system is measured by the difference between the actual position taken by a machine slide and the position called for. Accuracy is the joint effect of method, observer, apparatus and environment.

ACO: See *Adaptive Control Optimization.*

Acoustic Coupler: An electronic device that sends and receives digital data through a standard telephone handset. To transmit data, the digital signals are converted to audible tones that are acoustically coupled to a telephone handset. To receive data, the acoustically coupled audible signals are converted to digital signals.

Active Storage: Data storage locations in an NC control system which hold the data actively being transformed into motion. Contrast with *Buffer Storage.*

ADAPT: A computer-aided NC parts programming language comparable to APT but with more limited capabilities. Developed for medium-scale computers and essentially used for two-axis contouring.

Adaptive Control: A control method using sensors for real time measurement of process variables with calculation and adjustment of control parameters as a means of achieving near optimum process performance. The purpose of adaptive control is the optimization of the independent parameters (for example, speeds and feeds) consistent with process constraints such as quality of surface finish and cutter life.

Adaptive Control Constrained (ACC): A control system involving in-process measurement used to obtain maximum machine productivity by using limiting values for certain machine parameters such as torque or spindle deflection.

Adaptive Control Optimization (ACO): A control system involving in-process measurement and adjustment of variable cutting parameters to achieve optimum production conditions.

Address: In NC, a character or group of characters initiating a word and used to identify the data which follow in the word.

AIA: Aerospace Industries Association.

Algorithm: A procedure for accomplishing a given result by proceeding on a logical step-by-step basis. NC and computer programs are developed by this method.

Alphanumeric Code: A code consisting of letters, digits and associated special characters.

Analog: The use of physical variables, such as distance, rotation, or voltage, to represent and correspond with numerical variables that occur in a computation; contrasts with *Digital.* In NC, a system which utilizes electrical voltage magnitudes or ratios to represent physical axis positions.

Analog-to-Digital (A/D) Converter: A hardware device which senses an analog signal and converts it to a representation in digital form.

ANSI: American National Standards Institute.

APT: Automatically Programmed Tools. A computer-aided programming language which describes the part illustrated on an engineering drawing and takes the form of a sequence of statements that define the part geometry, cutter operations, and machine tool capabilities. Initially developed for 3-, 4-, and 5-axis milling machines but presently is capable of a wider range of applications including turning and point-to-point work.

ARELEM: Acronym for **AR**ithmetic **ELEM**ent. A part of the APT processor that calculates the cutter locations based on the cutter motion commands and the canonical forms of the geometrical surfaces.

ASCII: American Standard Code for Information Interchange. One of two major standard codes used for information interchange among data processing systems, communication systems, and associated equipment. It uses a coded character set consisting of 128 unique, 7-bit binary coded characters.

23.2 NC Vocabulary

Assembler: A computer program which converts a symbolic assembly language program into an executable object (binary-coded) program.

Assembly Language: An operation language composed of brief expressions which is translated by an assembler into a machine language.

Assembly Program: A program which translates the programmer's symbolic language to machine language, assigns absolute addresses to instruction and data words, and integrates subroutines into the main routine.

Automated Process Planning: Creation of process plans, with computer assistance either partially or totally, for items in a given family.

Automatic Acceleration and Deceleration: A control system feature providing for smooth changes in the velocity of the machine tool slide.

Automatic Programming: Any technique whereby a digital computer transforms programming from a form that is easy for a human being to produce into a form that is efficient for the computer to carry out.

Automatic Tape Rewind: A control system feature that causes the input tape to be rewound to the initial starting block after reaching the end of the program.

AUTOSPOT: Acronym for **AUTO**matic **S**ystem for **POS**itioning **T**ools. A general-purpose computer program designed to aid the parts programmer in preparing instructions for NC machine tools. Point-to-point capability only.

Auxiliary Function: A function of a machine control other than the control of the coordinates of a workpiece or tool. Usually on/off type operations

Axis: A general direction along which the relative movements of the tool and workpiece occur. One of the reference lines of a coordinate system.

Axis Inversion: See *Mirror-Image Programming.*

B-Axis: An angle defining rotary motion around the Y-axis such that positive *b* is in the direction to advance a right-handed screw in the +Y direction.

Backlash: A relative movement between interacting mechanical parts resulting from looseness and deflections.

Base: A quantity used implicitly to define systems of representing numbers by positional notation. See *Radix.*

Batch Processing: A method of processing jobs on a computer where they are organized and handled one at a time. Contrast with *Time Sharing.*

Baud: A unit of signaling speed equal to the number of discrete conditions of signal events per second. Used as a measure of serial data flow between a computer and/or communication devices.

Binary: (1) Pertaining to a characteristic or property involving a selection, choice, or condition in which there are two possibilities. (2) Pertaining to the number system with a radix of two. (3) A system for describing numbers using only two digits (zero and one).

Binary-Coded-Decimal (BCD) Notation: A number code in which a four-digit binary number is used to represent each digit in the decimal numbering system.

Binary Digit: In binary notation, either of the characters zero or one. It is equivalent to an "on" or "off" condition, or to a "yes" or "no."

Bit: (1) An abbreviation of **B**inary dig**IT**. (2) A single character of a language employing exactly two distinct kinds of characters. A bit, for instance, can be the absence or presence of a hole in paper tape.

Block: A group of words that contains all the instructions for a single operation. In a positioning system, a block will include the coordinates of the position, together with all the instructions for auxiliary functions necessary to complete an operation. The blocks are separated by an end-of-block character.

Block Address Format: A tape programming method for NC systems in which only the instructions that need changing are punched into the tape.

Block Delete: A feature providing for the skipping of certain blocks by programming a slash (/) code immediately ahead of the block. Useful when the operator desires to omit certain cuts on a particular part configuration.

Block Length: The total number of records, words or characters contained in one block.

BTR (Behind the Tape Reader): A method of inputting data directly into a machine control unit from an external source other than a tape reader.

Buffer Storage: A place where information from a block of tape is electronically saved or stored so that it can be transferred to active storage instantly. The next block is then put into the buffer storage while the previous command is being performed. This avoids waiting for the tape to go through the tape reader. Contrast with *Active Storage.*

Bug: An error or flaw in a program making it incapable of performing the objectives for which it was written.

Bulk Memory: A memory device for storing large quantities of data, for example, disk, drum, or magnetic tape. This type of memory is not programmable, as is core memory.

Byte: A series of binary bits which are operated on as a unit in a computer. A byte may be comprised of eight, twelve, or sixteen bits, for example. See *K.*

CAD: See *Computer-Aided Design.*

CAM: See *Computer-Aided Manufacturing.*

C-Axis: An angle defining rotary motion around the Z-axis such that positive c is in the direction to advance a right-handed screw in the +Z direction.

Canned Cycle: In NC, a fixed function in hardware or software in which several operations are performed in a predetermined sequence and ending with a return to the beginning condition. See *Macro.*

Cartesian Coordinates: A system of two or three mutually perpendicular axes along which any point can be located in terms of distance and direction from any other point.

Cathode Ray Tube (CRT): An electronic device containing a screen on which graphic or printed information may be displayed.

Central Processing Unit (CPU): The basic memory or logic of a computer that includes the circuits controlling the processing and execution of instructions.

Chad: The pieces of material that are removed when punching holes in tape or cards.

Channel: A path parallel to the edge of a tape along which information may be stored by means of the presence or absence of magnetic areas or of holes, singly or in sets. Also known as *Level.*

Character: One of a set of elementary marks, such as numerals or alphabetic letters, which may be combined to express information. A character includes all the marks, such as a group of holes punched in one row of a tape, which are necessary to completely identify it.

Chip: Small piece of semiconductor material on which electronic components are formed. Integrated circuits are formed on chips.

CIMS: See *Computer Integrated Manufacturing System.*

Circular Interpolation: The simultaneous and coordinated control of two axes of motion such that the resulting cutter path describes the arc of a circle.

CL Information: Stands for Cutter Location and describes the coordinates of the path of the center of the cutter resulting from a basic computer program. This information is common to all machine-tool-system combinations and is the input to the postprocessor.

Closed Loop System: A control system in which the output, or some result of the output, is measured and fed back for comparison with the input for the purpose of reducing any difference between input command and output functional response. Contrast with *Open Loop System.*

CNC: See *Computer Numerical Control.*

Code: The system of organized information that can be understood and acted upon by a control system, computer or data processing equipment.

Code Conversion: A process for changing the bit grouping for a character in one code into the corresponding bit group for a character in a second code.

Command: A signal from a machine control unit initiating one step in the execution of a complete program.

Communication Link: The physical means of connecting, transmitting and receiving data.

Compatibility: The degree to which tapes, languages, and programming can be interchanged among various machine tools and NC systems.

Compensation: When contouring, compensation is a displacement, always normal to the cutting path and workpiece programmed surface, to account for the difference between the actual and the programmed radius or diameter of the cutting tool.

Compile: To convert a computer program written in a high-level language such as *FORTRAN* into the binary-coded instructions that the computer can interpret.

Computer-Aided Design (CAD): The use of computers to aid in the design of products.

Computer-Aided Manufacturing (CAM): The use of computers to assist in any or all phases of manufacturing. NC is a subset of CAM.

Computer Graphics: A man-oriented system which uses the capabilities of a computer to create, transform and display pictorial and symbolic data.

Computer Integrated Manufacturing System (CIMS): Also known by several other names such as Flexible Manufacturing Systems and Computer Managed Parts Manufacturing. A multi-machine manufacturing complex linked by a material handling system and including features such as tool changers, load/unload stations, etc. Dissimilar workpieces are typically introduced into the system, then transported randomly and simultaneously to the NC machine tools and other processing stations, all under the control of a supervisory computer.

Computer (Computerized) Numerical Control (CNC): A self-contained NC system for a single machine tool utilizing a dedicated computer controlled by stored instructions to perform some or all of the basic NC functions. The usage of punched tape and tape readers is eliminated, except for possible use as a backup capability in the event of computer failure. It may become part of a DNC system through a direct link to a central computer.

Console: Part of a computer or NC machine tool system used for communication between the operator and the computer or machine tool.

Continuous Path: An NC machine type in which the rate and direction of relative movement of machine members is under continuous numerical control such that the machine travels through the designated path at the specified rate.

Contour Control System: A system in which the cutting

tool path is continuously controlled by the coordinated and simultaneous motion of two or more axes. Also called contouring.

Control System: An arrangement of interconnected elements interacting to maintain some condition of a machine or to modify it in a prescribed manner.

Controller: An apparatus of unitized or sectional design, through which commands are introduced and manipulated. A program controller has the following functions: data computation, encoding, storage, readout, process computation and output. See *Director.*

Conversational Mode: Communication between a terminal and the computer in which each entry from the terminal elicits a response from the computer and vice versa.

Coordinate Dimension: See *Absolute Dimension.*

Coordinate Dimension Word: A word defining an absolute dimension with respect to a specified reference zero.

Coordinates: See *Cartesian Coordinates.*

Cornering: Suddenly changing the direction of tool travel from one straight path to another.

CPU: See *Central Processing Unit.*

CRT: See *Cathode Ray Tube.*

Cursor: Visual movable pointer used on a CRT.

Cutter Compensation: A feature on some NC machines which gives the operator freedom to modify in a direction normal to the programmed tool path for changes in cutter radius, length or deflection.

Cutter Offset: The distance from the part surface to the axial center of a rotary cutter or to the center of a radius. The difference between the part surface and the cutter path during a machine operation.

Cutter Path: The path described by the center of a cutter in order to generate the desired part configuration.

Cycle: (1) A space or time interval during which a set of events or phenomena is completed. (2) A set of operations completely performed in a predetermined order.

Data: A representation of facts, concepts or instructions in a formalized manner suitable for communication, interpretation or processing by humans or by automatic means.

Data Acquisition: (1) Acquisition, evaluation and recording of data. (2) Identifying, isolating and gathering source data in a usable form to be centrally processed.

Data Bank: A comprehensive collection of libraries of data for computer processing, and stored on drum, disk or other storage media.

Data Base: A collection of data fundamental to an enterprise. Comprised of comprehensive files of information having predetermined structure and organization, and suitable for communication, interpretation or processing by humans or automatic means.

Data Conversion: Changing the format, method of storage, language, coding, symbolism or general form of information without changing the intelligence or logic content.

Data Link: The communication lines, modems and communication controls of all stations connected to the line used in the transmission of information between two or more stations.

Data Set: An electronic device providing an interface for the transmission of data to remote stations. See also *Acoustic Coupler.* The terms Modem and Data Set are often used interchangeably.

Dead Band: The range through which an input can be varied to the servo portion without initiating response at the machine tool. Generally, the narrower the dead band, the better the response of a machine-tool-system combination. Analogous to mechanical backlash. Also known as *Dead Zone.*

Dead Zone: See *Dead Band.*

Debug: Debugging is the process of detecting, locating and eliminating programming errors. Most programs of any complexity have to go through a debugging process.

Deceleration Distance: The calculated distance for deceleration of an axis of motion to avoid position overshoot.

Decimal Code: A code in which each allowable position has one of ten possible states.

Decimal Digit: One of the integers 0 through 9 when used in the scale of ten.

Decoder: A device which translates data from a coded form to an analog or other easily recognized form without significant loss of information.

Dedicated Computer: A computer devoted exclusively to a singular machine or application.

Delete Character: A character used primarily to obliterate any erroneous or unwanted characters.

Diagnostic Routine: A preventive maintenance check of key NC system components by use of a special programmed tape and/or electronic troubleshooting instruments. Specifically designed to locate and identify errors and malfunctions when they occur.

Digit: (1) One of the integers 0 through 9 when used for numbering in the scale of ten, regardless of position in the type of code in which they appear. (2) A character in any number system that may be used singly or in combination with other digits.

Digital: Information and values expressed in discrete terms. In a digital computer such terms are generated by a

combination of binary on/off or positive/negative signals. This is the opposite of analog, where a fluctuating signal strength determines the fluctuations of values.

Digital Input Data: Information supplied to a machine control unit or director in the form of digits, quantized pulses, or some other coding elements.

Digital-to-Analog (D/A) Converter: A device which transforms digital data into analog data.

Digitizer: A device which gives a digital representation of the value of an analog quantity.

Direct Numerical Control (DNC): The use of a shared computer for distribution of part program data via data lines to remote machine tools. DNC systems will typically contain provisions for collection, display, or editing of part programs, operator instructions, or other data related to the NC system.

Director: That portion of an NC system which receives the input data signals, and converts and amplifies these signals so as to make them usable by the power servos or control elements in the machine. Also known as *Machine Control Unit* or *Controller.*

Discrete Jog: Movement of a selected axis for some predetermined distance and direction. Used for repositioning the machine setup and for precise movement of the tool for checking purposes.

Disk Storage: The storing of data in the form of magspots on thin, circular, metal plates that have been ed on one or both sides with magnetizable material. ..e data are stored and retrieved by read-write heads positioned over the face of the disk.

DNC: See *Direct Numerical Control.*

Downtime: Time interval during which a device is malfunctioning or is in the process of being debugged.

Dwell: A timed delay of programmed or established duration.

Edit: To modify the form or format of data; for example, to add or delete characters.

Editor: A program permitting a user to create new or to modify existing data files.

EIA: Electronic Industries Association. An organization that has promulgated many standards pertaining to NC.

Encoder: An electromagnetic transducer commonly used to convert angular or linear position to digital data. See also *Resolver.*

End of Block (EOB): A symbol or character punched on the tape that denotes the end of one block of data. Used to stop the tape reader after a block of information has been read.

End of Program: A miscellaneous function (m02) indicating the last block in a program and the completion of a workpiece. Stops spindle, coolant, and feed after completion of all commands in the block. Used to reset control and/or machine.

End of Tape: A miscellaneous function (m03) which stops spindle, coolant, and feed after completion of all commands in the block. Used to reset control and/or machine.

EOB: See *End of Block.*

Error: The difference between an indicated and the desired values of a measured signal.

Error Register or Counter: A device for accumulating and signaling the algebraic difference between the quantized signal representing the desired machine position and the quantized signal representing the instantaneous position of the machine.

EXAPT: Acronym for **EX**tended subset of **APT**. An APT language processor developed in Europe by a German group. The most commonly used EXAPT processors are for point-to-point and lathe work.

External Storage: A storage unit such as punched tape or a floppy disk which is external to the computer. Also known as Auxiliary Storage.

Feed Holes: Holes which are punched in paper tape that enable the tape to be driven by a sprocket wheel.

Feed Rate: A term used to quantify the rate of movement of a machine element, expressed as a unit of distance relative to time or other machine function such as spindle rotation, table stroke, etc.

Feed Rate Number (FRN): A coded number which describes the feed rate. The coding method may differ among machines and control systems.

Feed Rate Override: A manual function which allows the operator to modify the programmed feed rate by a selected multiplier. This can be done on a percentage basis on some machines or a completely new feed rate on others.

Feedback: Information returned from the output of a machine or process for use as input in subsequent operations.

Feedback Device: A control system element which converts linear or rotary motion to an electrical signal for comparison to the input signal, for example, *Resolver, Encoder, Inductosyn.*

Feedback Loop: The part of a closed-loop system which enables the comparison of response with command.

Field: A set of one or more characters, not necessarily in the same word, which is treated as a unit of information.

Fixed Block Format: An NC tape format in which the number and sequence of words and characters appearing in successive blocks are constant. Note that the number of

characters is always the same; thus, all blocks are the same length. Contrast with *Variable Block Format.*

Fixed Cycle: A preset series of operations which direct machine axis movement and/or cause spindle operation to complete such actions as boring, drilling, tapping, or combinations thereof.

Fixed Sequential Format: An NC tape format whereby each word in the format is identified by its position. Words must be presented in a specific order and all possible words preceding the last desired word must be present in the block.

Fixed Zero: A reference position of the origin of the coordinate system; typically characteristic of machines having absolute feedback elements.

Fixture Compensation: A control feature that permits the alignment of a machine tool to a fixture in lieu of changing the fixture location to align with a machine tool. The control automatically compensates for changing alignment values on machine tools with rotary axis motion.

Flexowriter: An automatic typewriter that incorporates an eight-track tape reader and punch. Made by the Friden Corporation for preparation of punched tape.

Flip-Flop: A physical element or circuit having two stable static states, either of which may be induced by means of suitable input signals.

Floating Zero: (Not to be confused with *Zero Offset*) A characteristic of an NC machine tool control permitting the zero reference point of an axis to be established readily at any point in the full travel of the machine tool. The control retains no information on the location of any previously established zeros. Contrast with *Absolute Zero Point.*

Floppy Disk: A magnetic based disk used to store information. Used for data input to NC machine control units.

Following Error: The distance lag between the actual position and the command position in a contouring machine at any specific time.

Format: The physical arrangement of data on a program tape and the overall pattern in which it is organized and presented.

Format Classification: An abbreviated notation of the codes used to identify particular systems; it consists of the three following parts: Format Classification Shorthand, Format Classification Detailed Shorthand, and Itemized Data of the Format Contents and Machine Specifications.

FORTRAN: Acronym for **FOR**mula **TRAN**slation, a universal computer language in which many NC master programs are written.

Fourth Generation: The change in NC control logic technology to include computer architecture.

FRN: See *Feed Rate Number.*

Full Range Zero Offset: A feature on some NC systems which gives the ability to introduce a dimension which will always be added to the tape command dimension which in turn results in the effect of moving the programmed zero point. Also known as Full Range Floating Zero.

g-Function: A preparatory code on a program tape addressed by the letter *g* that indicates a special function or cycle in an NC system.

Gain: The amount of increase in a signal as it passes through a control system or a control element. If a signal becomes smaller, it is said to be attenuated. The gain in a control system refers to its sensitivity and its ability to raise the power of a signal to a required output.

Garbage: Erroneous, faulty, unwanted or extraneous data in a computer or NC program.

Gate: A logic circuit with one output and one or more inputs, designed so that the output is energized only when certain input conditions are met.

General Processor: Also referred to as master programs. This is the program containing the basic intelligence for NC work that is stored in computer memory before individual workpiece programs can be processed. APT and ADAPT are examples of general processors. Many machine tool builders, machine control unit manufacturers, and service organizations have prepared and make available general processors.

Graphical Input: Input to NC systems which comes directly from a graphic description such as lines drawn on a cathode ray tube or information obtained by a scanner from drawings.

Group Technology: (1) The classification and coding of parts on the basis of design similarities. (2) The grouping of parts into production families based on processing similarities so that the parts in a particular "family" could then be processed together. (3) The grouping of diverse machines together to produce a particular family of parts.

Hardware: Physical equipment, as opposed to the program or method of use, for example, mechanical, magnetic, electrical or electronic devices. Contrast with *Software.*

Hardwired: An NC system which handles data input, sequencing, control functions and formats by fixed and committed circuit connections. Changes can only be made by changing physical components or interconnections.

Hexadecimal: A numbering system with a radix or base of sixteen. Valid digits range from 0 (zero) through F, where F represents the highest units position. Useful in computers because of the economy of memory space and simple representation in binary form. *Binary* and *Octal* are the other most frequently used systems.

Hierarchy: A group or series arranged in a rank order.

Hold: An untimed delay in the program, terminated by an operator or interlock action.

Hollerith: The set of codes used in punch cards utilizing 12 rows per column and usually 80 columns per card.

Home Position: A fixed location in the basic coordinate axes of the machine tool. Usually the point at which everything is fully retracted for a tool or pallet change.

Hunting: A condition in the control system in which a machine component moves slightly back and forth seeking to null out to an absolute stop condition. Generally, considered an unsatisfactory situation.

Hysteresis: The difference between the response of a unit or system to an increasing signal and the response to a decreasing signal.

IC: See *Integrated Circuit.*

IEEE: Institute of Electrical and Electronic Engineers.

Inch/Metric Input: The capability of selecting inch or metric programming on an NC system without the need to change the feedback devices. Selection is by switch or by program controls.

Incremental Coordinates: Coordinates measured from the preceding value in a sequence of values.

Incremental Dimension: A dimension defined with respect to the preceding point in a sequence of points.

Incremental System: An NC system in which each coordinate or positional dimension, both input and feedback, is taken from the last position rather than from a common datum point, as in an absolute system.

Indexing: One-axis movement of an NC system component to a precise point through numeric commands.

Inductosyn: Trademark for the Farrand Controls resolver, in which an output signal is produced by inductive coupling between metallic patterns in two glass members separated by a small air space. Produced in both rotary and linear configurations.

Input: The actual transfer of information into a computer or machine control unit by an appropriate medium such as punched tape.

Input/Output (I/O) Device: Input/output equipment used to communicate with a computer or control system.

Input Resolution: The smallest dimension, increment that can be programmed as an input to the system.

Input Translator: A phase whereby the source statements are read one at a time, checked for errors in punctuation, ordering, syntax and incomplete statements.

Instruction: A statement which tells the director to cause some operation to be performed.

Instruction Set: The list of machine language instructions that can be performed by a computer.

Integrated Circuit (IC): An electronic circuit that is packaged as a single small unit, ranging in size from about 0.3 inches square to about 2 inches square. The circuits vary in complexity and function from simple logic gates to microprocessors, amplifiers and special devices such as A/D and D/A converters. If the integrated circuit is constructed on a single semiconductor substrate, it is called monolithic. If it is constructed of several independently fabricated circuits that are interconnected, it is called hybrid. The sizes of the circuits are further classified by the terms Small-Scale Integration (SSI), Medium-Scale Integration (MSI), Large-Scale Integration (LSI), dependent on the complexity of the circuit. Slang terms for an integrated circuit are "Bug" and "Chip."

Interface: The medium by which two separate elements are joined. There is an interface between a machine control unit and a machine tool comprised of electrical circuitry and drive motors. If a computer directly controls a machine tool, there is an appropriate interface.

Interlock: An arrangement in the control of a machine to prevent further operations until the operation in process is completed.

Interpolation: The insertion of intermediate information based on assumed order of computation. For example, cutter paths are controlled by interpolation between fixed points by assuming the intermediate points are on a line, a circle or a parabola.

Interpolator: A device for defining the path to be followed, and the rate of travel of a cutting tool or of a machine-tool slide or element, when supplied with a coded mathematical description (circular, linear, parabolic, etc.) of the same. It provides the intermediate points between programmed end points to produce smooth curves or straight lines.

I/O: See *Input/Output Device.*

ISO: International Organization for Standardization.

Iteration: Repetitive computations in which the output of each step is the input to the subsequent step.

Jog: The manual movement of a selected axis in either direction at varying feed rates for the purpose of accomplishing a small movement of the axis.

K: K comes from the French "Kilo" meaning thousand. In data processing, K is used when defining memory locations to mean 1,024 locations in which information is stored and processed. The memory capacity of computers is normally a power of two, thus an 8K computer memory has 8 times 1,024, or 8,192 locations.

Keypunch: A keyboard actuated device used to punch holes in cards to represent data.

23.2 NC Vocabulary

Language: A defined group of representative characters and symbols with rules necessary for their interpretation and application. When applied according to the rules, a language is meaningful to a computer, NC system, or data processing devices.

Language Translator: A general term for any assembler, compiler or other routine that accepts statements in one language and produces equivalent statements in another language.

Lead Screw Compensation: Automatic compensation for measured lead screw errors.

Leader: Blank tape which appears ahead of and after a section of coded tape.

Leading Zero: Redundant zeros added to the left side of a number to fix the position of the decimal point.

Level: Same as *Channel.*

Linear Interpolation: The approximation of curves of circular arcs by a series of straight lines or chords which combined produce a smooth curve (within tolerances) along the contour machine part. Linear interpolation may be performed by the contouring control itself, or it may be externally performed by manual or computer-assisted means.

Loop Tape: A short length of punched tape joined end-to-end in the form of a loop for continuous or repetitive reading.

m-Function: Similar to a g-function except that the m-functions control miscellaneous actions of the machine tool, such as turning coolant on and off or operating power clamps.

Machine Control Unit (MCU): See *Director.*

Machine Datum: The point in a machine system used as a basis for establishing a coordinate system.

Machine Language: A set of symbols, characters or signs (and the rules for combining them) which convey to a computer the instructions or information to be processed. This language is unintelligible to people unless the symbols and the rules for their use are understood. Special equipment is usually needed to convert this language from the form in which it is stored in the computer to a form perceptible to people.

Machine Zero: The origin of the coordinates in the machine system.

Machining Center: A machine tool, often numerically controlled, that can automatically drill, ream, tap, bore and mill workpieces and is frequently equipped with an automatic tool-changing system.

Macro: A group of instructions that are organized as a group and can be called as a unit.

Magic 3: A method of coding speeds and feeds specified in EIA standards.

Magnetic Tape: Tape constructed from metal or plastic and coated with a magnetic material that can store information at a much higher density than other media such as paper tape.

Maintenance: Any activity intended to eliminate faults or to keep hardware or programs in satisfactory working condition, including tests, measurements, replacements, adjustments and repairs.

Management Information Systems: Management performed with the aid of automatic data processing.

Manual Data Input: A means for the manual insertion of commands into the NC control system by means other than program tape.

Manual Feed Rate Override: See *Feed Rate Override.*

Manual Mode: A mode of operation in which NC machine tools can be completely controlled by manually initiating movements and/or cycles.

Manual Part Programming: See *Part Programming, Hand or Manual.*

Manuscript: An ordered list of NC program instructions. See also *Part Program.*

Memory: A term referring to the equipment and media used for holding information in machine language in electrical or magnetic form. See *K.*

Microcomputer: A computer that is constructed using a microprocessor as the basic element.

Microinstruction: A basic or elementary machine instruction.

Microprocessor: A basic element of a central processing unit that is a single integrated circuit. A microprocessor has a limited instruction set which is usually expanded by microprogramming. A microprocessor requires additional circuits to become a suitable central processing unit. See *Microcomputer.*

Microprogramming: A method of operation of the CPU in which each complete instruction starts the execution of a sequence of instructions, called microinstructions, which are generally at a more elementary level.

Microsecond: One-millionth of a second.

Millisecond: One-thousandth of a second.

Mirror-Image Programming: A feature of some machine control units that provides for the reversing of all instructions programmed for a specific axis (usually X) by means of a switch. This means that a single program tape can produce two mirror-image parts.

Miscellaneous Function: One of a group of special or auxiliary functions of a machine such as spindle stop. coolant on. clamp. See *g. m.* and *t* functions.

Mnemonic Symbol: An alphanumeric designation chosen to assist the programmer in remembering. such as mpy for multiply.

Modem: In data transmission. a modulator/demodulator device which converts data from one form to another for equipment compatibility.

Mylar: A DuPont trademark for polyester film. often used as a base for magnetically coated or perforated information media.

Nanosecond: One-billionth of a second.

NC: See *Numerical Control System.*

Noise: An unwanted stray signal in a control system which can interfere with normal operation of a machine control unit or computer.

NMTBA: National Machine Tool Builders Association.

Number System: A code for expressing numerical data in which the symbols and rules for their use are defined.

Numerical Control (NC) System: A system in which actions are controlled by the direct insertion of numerical data at some point. The system must automatically interpret at least some portion of this data.

Numerical Data: Data in which information is expressed by a set of numbers or symbols that can only assume definite discrete values.

Object Deck: A deck of tabulating cards containing the condensed computer instructions for handling a specific general processor. The programmer usually writes only one instruction per card. These instructions are then processed by the computer and condensed to an object deck where a multitude of instructions may be included on a single card. It is the customary practice for program writing services to furnish only the object deck to the customer. In this manner the service is furnishing a specific capability but is not releasing its proprietary methods and logic.

Octal: Pertaining to a number system with a radix or base of 8. The system is used in computers because of its economy of memory. ease of conversion to other number bases, and simple application to binary logic circuitry. *Binary* and *Hexadecimal* are the other frequently used systems with computers.

Offline Operation: Operation of peripheral equipment independent of the central processor of a computer system.

Offset: A displacement in the axial direction of the tool which is the difference between the actual tool length and that established by a programmer.

Ones Complement: The radix-minus-one complement in binary notation.

Online Operation: Applies to computer operations and calculations which are performed by the computer itself or the major portion of the computer.

Open Loop System: A control system that has no means for comparing the output with the input for control purposes. that is. there is no feedback. Contrast with *Closed Loop System.*

Operation Number: A number indicating the position of an operation in a sequence of operations.

Optimize: The rearrangement of instructions of data in NC or computer applications to obtain the best balance between operating efficiency and best use of hardware capacity.

Optional Stop: A miscellaneous function command similar to a program stop. except that the control ignores the command unless the operator has previously pushed a button to recognize the command.

Origin: A reference point whose coordinate values are zero.

Output: The opposite of input. The actual transfer of processed information out of a computer. It may be output onto tabulating cards. punched tape. magnetic tape. printed sheets. drum storage or even to another computer.

Overshoot: The amount of overtravel that takes place when a cornering maneuver is made at high feed rates by the machine tool traveling member. The overshoot may be caused by the inertia of the mechanical drive system. Contrast with *Undercut.*

Paper Tape: See *Punched Tape.*

Paper Tape Reader: A device that senses and translates the holes in perforated tape into electrical signals.

Parabolic Interpolation: A mode of contouring control utilizing parabolic arcs to approximate curves by automatic means within the control system. The arcs are also blended automatically. This method of interpolation is particularly applicable to mold or die work where free form shapes can be generated with a minimum number of program steps.

Parallel Entry: All characters displayed simultaneously as opposed to serial.

Parity Check: A method of automatically checking to reduce possibility of tape errors caused by a malfunctioning tape punch. In the EIA method of character coding. the parity column will have a punch if the character itself is comprised of an even number of punches Thus any row of tape will always have an odd number of holes (not counting the sprocket holes). ASCII characters will always have an even number when the parity check hole is included. The

incorporation of a parity check feature makes it possible to automatically stop the machine when a punched tape error is detected.

Park: A programmed instruction for moving the tool to a location safe for conducting tool and workpiece inspection

Part Program: An ordered set of instructions in a language and form required to cause operations to be effected under automatic control, which then is either written in the form of a manuscript on an input medium or stored as input data for processing in a computer to obtain a manuscript.

Part Programming, Computer: The preparation of a manuscript in computer language and format required to accomplish a given task. The necessary calculations are performed by the computer.

Part Programming, Hand or Manual: The preparation of a manuscript in machine control language and format required to accomplish a given task. The necessary calculations are performed manually.

Pattern Manipulation: A part programming feature which permits the programmer to reuse a previously programmed pattern at other positions on the part.

Peripheral Equipment: Any unit of equipment, distinct from the central processing unit, which may provide the system with outside communication.

Phase Shift: A time difference between the input and output signal of a servo loop.

Picosecond: One-millionth of one microsecond.

Plotter: A device which will draw a facsimile of coded data input such as the cutter path of an NC program. Some plotters make "hard" paper copy and others use a CRT scope.

Point-to-Point Control System: See *Positioning Control System.*

Position Readout: A visual display of the absolute position of a machine axis. Derived from a position feedback device normally attached to the lead screw of the machine.

Position Sensor: A device for measuring a position, and for converting this measurement into a form convenient for transmission, as a source of feedback. See *Transducer.*

Positioning Control System: Discrete or point-to-point control, in which the controlled motion is required only to reach a given end point, with no path control during the transition from one end point to the next.

Positioning Time: The time required to rapid traverse the tool from one coordinate to another.

Postprocessor: A computer routine for translating the output of a general programming routine into a machine language suitable for a specific NC machine.

Precision: Closeness of agreement among repeated measurements of the same characteristics by the same method under the same condition. See *Accuracy* and *Reproducibility.*

Preparatory Function: A command changing the mode of operation of the control, such as from positioning to contouring, or calling for a "canned cycle" of the machine. A command to establish the mode of operation, which is generally noted at the beginning of a block and consists of a letter character "g" plus a 2-digit number.

Preset Tool: A cutting tool placed in a holder so that a predetermined geometrical relationship will exist with a gage point. Tooling is adjusted offline to be compatible with a programmed tool path.

Preventive Maintenance: Maintenance specifically intended to prevent faults from occurring during subsequent operation.

Printer: An output mechanism which prints or typewrites characters in either parallel or serial entry.

Printout: A printed sheet giving all the data of a program that has either been manually or computer processed. The printout is used for reference and visual checking. Normally the printout will be made at the same time a tape is punched.

Processor: (1) That portion of a computer which controls the operation input and output devices and operates on the received, stored and transmitted data. Its circuitry includes the functions of memory, logic, arithmetic and control. (2) The software required to implement some function of a computer. Generally used in connection with the implementation of a source language.

Program: A set of instructions that defines a desired sequence of conditions for a process or function, and the operations required between these conditions. See *Part Program* and *Manuscript.*

Program Stop: A miscellaneous function command to stop the spindle, coolant, and feed after completion of other commands in the block. It is necessary for the operator to push a button in order to continue with the remainder of the program.

Programmer: In NC work there are two important types of programmers. A workpiece programmer writes the instructions for the computer to act upon to develop a specific program tape. A computer programmer develops the routines that give the computer the basic intelligence to act upon instructions when they are prepared by the workpiece programmer.

Programming: Preparing a detailed sequence of operating instructions for a particular problem.

Programming Language: A language used by the programmer to describe the problem in terms associated with the problem itself.

PROM: Programmable Read Only Memory. A memory that can be programmed only by special routines. Once

programmed with permanent data, such as a mathematical formula, it becomes a ROM or Read Only Memory.

Pulse: A pattern of variation of a quantity, such as voltage or current, consisting of an abrupt change from one level to another, followed by an abrupt change to the original level.

Punched Card: A card of constant size and shape, suitable for punching in a meaningful pattern and for mechanical handling. The punched holes are usually sensed electrically or mechanically.

Punched Tape: An input medium comprising a paper or plastic tape into which a pattern of holes is punched so as to represent data.

Quadrant: One of the quarters of the rectangular or Cartesian coordinate dimensioning system.

Radix: Base or root; a number that is arbitrarily made the fundamental number of a number system. The quantity of different symbols required to express any integer in a number system.

Random Access: Indicates equality of access time to all memory locations, independent of the location of the previous memory reference.

Random Tool Selection: A feature permitting the next tool to be loaded from any position in an automatic tool changer as contrasted to loading from the next available location in the changer.

Rapid Traverse: Tool movement at maximum feed rate from one cutting operation to another.

Read: To sense the characters involved in numerical input information.

Read-In: Numerical display of input data, that is, what is presented by the coded tape to the control and not the actual position assumed by the machine. Commonly referred to, erroneously, as *Read-Out.*

Read-Out: A numerical display of the actual position of, for instance, a machine slide, as provided by some feedback device. May be digital visual display, punched tape, punched cards, automatic typewriter, etc. See *Read-In.*

Real Time: The ability of a computer to function and control a process as that process occurs. For example: A computer directly controlling the operation of a machine tool would be a real time application. If a computer generates a program tape and the tape is utilized at some later time, the computer is used in an "offline" application.

Rectangular Coordinates: A system of two or three mutually perpendicular axes along which any point can be located in terms of distance and direction from any other point.

Reference Block: A block within the program identified by an "o" (letter o) or "h" (letter h) in place of the word address "n" and containing sufficient data to enable resumption of the program following an interruption.

Reference Point: A point defined within the limits of travel to locate the spindle in relation to the part.

Relative Coordinates: See *Incremental Coordinates.*

Reproducibility: (1) The exactness with which measurement of a given value can be duplicated. (2) The ability of a system or element to maintain its output/input precision over a relatively long period of time. Also called repeatability. See *Accuracy* and *Precision.*

Rerun: A repeat of a machine run, usually because of a correction, an interrupt, or a false start.

Resolution: The shortest distance between two adjacent cutter locations which can be distinguished from each other by the NC system. Commonly available resolutions are 0.001 or 0.0002 or 0.0001 inch.

Resolver: A rotary or linear electrical feedback device used to feed back a signal to the machine control unit error detector. The resolver is usually on the end of a leadscrew of an NC machine tool. See *Encoder.*

Retrofit: Modification of a machine originally operated by manual or tracer control to one that operates by NC controls. The machine may require considerable alteration and repair so that the NC controls will function properly and accurately.

Routine: A set of instructions arranged in the correct sequence to direct the control computer to perform one of a series of operations.

Row: A path perpendicular to the edge of a tape, along which information may be stored by means of the presence or absence of magnetized areas, or of holes, singly or in sets.

s-Word: An NC program code preceded by the word "s" which determines spindle speed.

Sampled Data: Data in which the information content is ascertainable only at discrete intervals of time. Sampled data can be analog or digital.

Scanner: Equipment used to digitize coordinate information from a master and convert it into punched tape for later re-creation of the master shape on an NC machine.

SCR: See *Silicon Controlled Rectifier.*

Sculptured Surface: (1) A mathematically described surface consisting of a composite of interconnected, bounded, parametric surface patches, each patch representing an image of a unit square in parametric space. (2) Any free form, nonplanar surface often nonanalytic; the surfaces of complex shapes usually obtained by hand or sculpturing techniques.

23.2 NC Vocabulary

Second Generation: In NC, the period of technology associated with transistors.

Segment: That portion of a path joining two successive points stored in the position-storage medium.

Sensor: A transducer or other device whose input is a quantitative measure of some external physical phenomenon and whose output can be read by a computer.

Sequence Number: A series of numerals programmed on a tape and displayed as a Read-In. It is normally used to identify blocks or groups of blocks in a manuscript and is identified by the letter *n* as the address character.

Sequential: Items arranged in some predetermined logical order.

Serial: Items handled one after another rather than simultaneously.

Servomechanism: A power device for directly effecting machine motion. It embodies a closed-loop system in which the controlled variable is mechanical position. Usually some amplification is necessary between the relatively weak feedback signal and the strong command signal.

Setpoint: The final or target value of a controlled variable which is to be reached.

Set-up Time: Time required to adjust a machine and attach the proper tooling to make a particular product.

Sign Digit: A plus or a minus sign for arbitrarily designating the positive or negative characteristic of a coordinate.

Signal: Information transmittal from one point in a control system to another.

Silicon Controlled Rectifier (SCR): An electronic device that is generally used in control systems for high-power loads, such as for an electric heating element.

Skip: An instruction to proceed to the next instruction.

Software: All of the program manuscripts, tapes, decks of tabulating cards, methods sheets, flow charts and other programming documentation associated with computers and NC. Its counterpart is the physical hardware comprising the computer or NC system. Contrast with *Hardware.*

Softwired Numerical Control: See *Computer Numerical Control.*

Source Language: A computer input language designed for easy or convenient use which can be translated, interpreted and executed by a computer, using an appropriate processor. The output is in the language of the NC machine tool, usually as a punched tape.

Spindle Speed Override: A feature which allows the operator to modify the programmed spindle speed by a selected multiplier.

Spindle Speed Selection: A control function that provides control of spindle speed through input tape commands.

Static Behavior: The functioning of a control system under fixed or steady-state conditions as contrasted with dynamic behavior, which refers to behavior under changing conditions.

Steady State: A characteristic or condition exhibiting only negligible change over an arbitrarily long period of time.

Step-Change: A change from one value to another by a stepped increment as opposed to a smooth variation.

Stepping Motor: An electric motor in which the rotor moves in small fixed angular steps controlled by a sequence of electrical pulses to the stator windings. The angle through which the rotor turns depends on the number of applied pulses while the rotational speed depends on the rate of pulse application.

Stiction: The combination of adhesion (sticking) and friction which must be overcome to move a machine member from rest.

Storage Medium: A device into which information can be introduced, held and then extracted at a later time.

Stored Program Numerical Control: Usually the same as CNC. The distinguishing feature is an internal memory that can be altered by receiving new instructions. The physical configuration is not altered by programming.

Straight-Cut Control System: A system of control in which controlled cutting action occurs only along a path parallel to linear, circular or other machine ways.

Subroutine: A portion of the total NC program, stored in the computer's memory, and available upon call to accomplish a particular operation, usually a mathematical calculation. At its conclusion, control reverts to the master routine.

Swarf Cut: The removal of a large section of material such as clamping lugs or tooling pads from a part by cutting the material off the part with a profiling cutter pass.

Symmetry Switching: See *Mirror-Image Programming.*

Synchro: A wound-rotor magnetic induction transducer, capable of electrically transmitting or receiving angular positional information.

System: An organized collection of interdependent and interactive personnel, machines, and methods required to accomplish a set of specific functions.

t-Function: A code identifying a tool select command on a program tape. As with *m* and *g* codes, the *t* also appears as a lower case letter on a printout.

Tab: A nonprinting spacing action on tape preparation

devices, whose code is necessary to the *Tab Sequential Format.*

Tab Sequential Format: An NC tape format in which words are identified by the number of tab characters preceding the word in the block. The first character in each word is a tab character. Words must be presented in a special order, but all characters in a word, except the tab character, may be omitted when the command represented by that word is not desired.

Tape Editor: A means that allows the operator to replace, delete, or otherwise change one or more blocks of data.

Tape Feed: A mechanism for feeding tape to be read or sensed by the machine.

Tape Rewind: A feature that automatically returns the tape to the initial block of information. It will always be located in the last block if it is part of the tape input information.

Temporary Storage: Internal storage locations reserved for intermediate and partial results

Third Generation: In NC, the period of technology associated with integrated circuits.

Time Sharing: The use of a computer memory for two or more purposes during the same time period. Contrast with *Batch Processing.*

Tool-Change Time: The time to change from one type of tool to another. Used especially to describe automatic tool changers.

Tool Function: A command identifying a tool and calling for its selection either automatically or manually. The actual changing of the tool may be accomplished by a separate tool-change command.

Tool Offset: An incremental displacement correction for tool position parallel to a controlled axis.

Tooling: A set of required standard or special tools for the production of a particular part, including jigs, fixtures, gages, cutting tools, etc. Specifically excludes machine tools.

Track: A patch parallel to the edge of a tape along which information may be stored by means of the presence or absence of magnetic areas or of holes, singly or in sets.

Transducer: A device for converting one form of energy into another form; for example, a pneumatic signal into an electric signal.

Transistor: A device employing a semiconductor with three or more electrodes for controlling and regulating the flow of electrons; performs much the same functions as a vacuum tube.

Transistor-Transistor-Logic (TTL): A common logic configuration used in integrated circuits characterized by high-speed and noise immunity.

Translation: The changing of information from one form to another.

TTL: See *Transistor-Transistor-Logic.*

Turn Key System: An NC or computer system installed by a vendor who has total responsibility for building, installing and testing the system.

Turning Center: A lathe-type NC machine tool capable of automatically boring, turning, threading and facing parts; often equipped with a system for automatically changing or indexing cutting tools.

Undercut: A machine cut where the cutter failed to arrive at a programmed point following a command change in direction. Also called Undershoot. Contrast with *Overshoot.*

Universal Fixturing: A set of building-block-type components from which a fixture or fixture setup may be constructed.

Unwind: To reverse the direction of a screw or a gear for a period sufficient to reduce the torsional stresses due to windup.

Uptime: The percentage of total working time in which the NC machine is in satisfactory operation condition. Opposite to *Downtime*

USASCII: Same as *ASCII.*

Variable Block Format: An NC tape format which allows the number of words in successive blocks to vary. This applies to both *Tab Sequential* and *Word Address* programs. Contrast with *Fixed Block Format.*

Verify: To check, usually by automatic means, one typing or recording of data against another in order to minimize the number of human and machine errors in the data transcription.

Windup: Lost motion in a mechanical system proportional to the applied force or torque.

Word: An ordered set of characters referring to a unit of information. The normal unit in which information may be stored, transmitted, or acted upon.

Word Address Format: An NC tape format in which the addressing of each word in a block is done by one or more characters which identify the meaning of the word.

Workpiece Program: A program which gives the instructions for machining a specific workpiece. This should not be confused with computer master programs or processor languages which equip a computer to handle the individual workpiece programs.

23.2 NC Vocabulary

Write: The imparting or introduction of information into the memory or data input devices of a computer or control system.

X-Axis: The axis of motion that is horizontal and parallel to the work holding surface. If Z is horizontal, positive X is to the right looking from the spindle toward the workpiece. If the Z-axis is vertical, when looking from the spindle toward its supporting column(s) the positive X-axis is to the right on single column machines or forward on dual column or gantry machines. On machines generating a surface of revolution, such as lathes, X motions shall be radial, and normally the positive direction of motion shall be away from the center of revolution. Where the linear motion can cross the centerline of rotation, positive motion shall be in the direction of maximum displacement from the center of rotation.

Y-Axis: The axis of motion that is perpendicular to both X and Z. Positive Y is in the direction to make a right-handed set of coordinates, that is, +X rotated into +Y advances a right-handed screw in the +Z direction.

Z-Axis: The axis of motion that is parallel to the principal spindle of the machine. If there are several spindles, one shall be selected as the principal one. If there is no spindle, the Z-axis is perpendicular to the work holding surface. If the principal spindle can be swiveled or gimbaled, the Z-axis is parallel to the spindle axis when the spindle is in its zero position. Positive Z is in the direction from the work holding means toward the tool holding means. Positive Z motion increases the distance between the work and the tool.

Zero: The point from which all coordinate dimensions are programmed in an absolute system.

Zero Offset: (Not to be confused with *Floating Zero*) A machine control feature permitting the fixed zero point on an axis to be shifted readily over a specified range. The control retains information on the location of the "permanent" zero.

Zero Reset: See *Zero Synchronization.*

Zero Shift: Manually orienting the slides of an NC machine so that the zero point is shifted to any point within the range of the measuring system.

Zero Suppression: The elimination of nonsignificant zeros either before or after the significant figures in a tape command. The purpose is to reduce the number of characters that are required to be read.

Zero Synchronization: A technique which permits automatic recovery of a precise position after the machine axis has been approximately positioned by manual control.

SECTION 24

COMPUTER-AIDED MANUFACTURING TECHNOLOGIES

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COMPUTER-AIDED MANUFACTURING TECHNOLOGIES 24

INTRODUCTION

The introduction of computers into the manufacturing environment has revolutionized manufacturing technology. As computers have become more powerful with their increasing ability to perform complex calculations quickly and manage vasts amounts of data, they have found their way into numerous manufacturing applications including part design and analysis, production scheduling and control, inventory and cost accounting, process control, and optimization and machinability data analyses. Time-sharing computer networks have brought the computer to design engineers, process planners, production control personnel and, in many cases, out to the machine operators at the NC machine tools. The days when the computer was simply an accounting tool or a scientific research tool are gone. Every phase of the production process has been affected, and the future promises that even more work will be taken over by the computer. This should hopefully lead to design engineers being more creative, manufacturing engineers tackling more problems, and products being better engineered and produced more efficiently.

The earliest applications of computers in manufacturing came in the general accounting area (job control, inventory control, shipping/receiving, payroll, etc.). Engineering applications emerged in three general areas: design and drafting, planning and scheduling, and fabrication (see figure 24-1). The first applications were in computer-assisted drafting. Design analysis routines then emerged for evaluating the mechanical properties of the part. Today, this area is referred to as CAD, computer-aided design, and has seen the largest growth in commercial systems. The introduction of highly advanced interactive graphics (IAG) systems accelerated this growth. The designer using the IAG cathode ray tube (CRT) can change his design by trying a number of new design modifications. The interactive loop gives him almost instantaneous review of the effect of the modifications on his design, and the process can be conducted until a satisfactory design is obtained. The computer can then analyze the mechanical, structural and dynamic properties of the design before directing graphic plotters to make finished drawings. To date, the status of CAD has been restricted to special applications primarily in the aerospace and automotive industries where complex parts with contoured surfaces are designed. However, CAD has brought an enormous capability to the hands of the design engineer, and its expansion will continue with the emergence of new software, hardware and data bases.

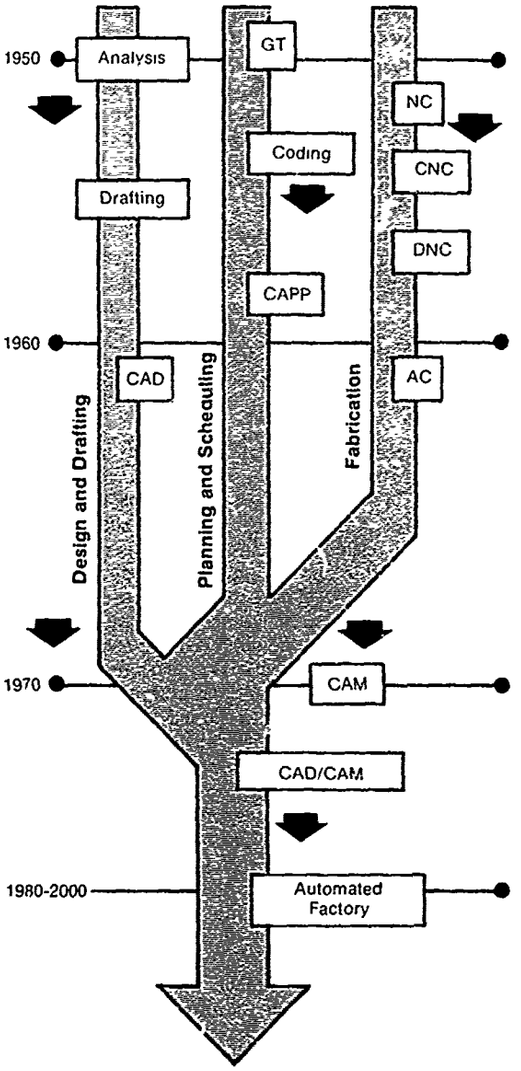


Figure 24-1 Historical development of CAD/CAM software concepts.

The influence of computers in production has been in two areas: manufacturing planning and manufacturing control. These two areas comprise what has come to be referred to as CAM, computer-aided manufacturing. Earliest CAM developments were in the planning area since production planning was chronologically the next step after part design and did not rely on the retrofitting or redesign of any hardware. The growth of computers in manufacturing control was dependent upon the growth of NC and NC machine tools. Early work in the planning area dealt with group technology (GT). Group technology classifies parts having similar design features and/or similar manufacturing sequences and has become one of the first formal disciplines to bring together part design and part manufacturing. Out of group technology have grown the concepts of part families, cellular manufacturing, part coding for manufacturing, computer-assisted process planning and centralized manufacturing data bases. Computer-assisted process planning generates the production operation sequence, tool layout, fixturing requirements and recommended cutting speeds and feed rates. Manufacturing data bases provide the raw information on tooling, machine tools and cutting performance to run process planning programs. Group technology, computer-assisted process planning and manufacturing data bases are discussed in more detail in the section "Computers in Manufacturing Planning."

The use of computers in manufacturing control grew out of NC technology. The preparation of NC tapes is one area which was enhanced with the introduction of computer-assisted NC programming languages (APT, CINTURN, TOOLPATH, etc.) and with the work done in interfacing CAD with CAM. It is now possible with some CAD/CAM systems to generate the NC tape directly from the designed part stored in the computer memory. Only slight revisions of the computer-generated tape are needed for inserting cutting speed, feed rate, coolant, etc. NC controllers have been modified to incorporate mini- and micro-computers. These control systems are now called computer numerical control (CNC). Computer networks for monitoring and controlling several machine tools, namely, direct numerical control (DNC), have been implemented. CNC and DNC are discussed in more detail in the section "Computers in Manufacturing Control."

A more advanced process control concept which has recently emerged from the research laboratories is adaptive control (AC). The concept of adaptive control is to monitor critical process performance responses, such as cutting forces, horsepower, cutting temperature and tool wear, and then to adjust the cutting parameters (that is, cutting speed, feed rate, depth of cut, etc.) on-line to maintain optimal cutting performance. Numerous research activities have been undertaken to develop reliable sensing systems, appropriate performance critera, workable controlling logic and high speed, on-the-floor computing capability. Not all the elements of the envisioned AC system are sufficiently developed for commercial use (for example, tool wear sensing), but a few workable systems have been demonstrated. These systems are the constraint-control type which monitors one critical response, such as horsepower or cutting forces, and adjusts one parameter (commonly the feed rate) when the critical (maximum) level of the response is reached. In constraint-control AC, feasible cutting is assured; however, optimal cutting performance is not necessarily maintained.

Research work is being done on the performance index-control type system which monitors not only the constraints of the process but also some economical or productivity performance index, and then continually adjusts several cutting parameters to maintain optimal performance. Adaptive control is discussed in more detail in the section Computers in Manufacturing Control."

COMPUTERS IN MANUFACTURING PLANNING

Group Technology

Introduction

Group technology is a manufacturing philosophy whose basis is the recognition that similarities occur in the design and manufacture of discrete parts. Despite the tendency to consider each manufactured part as being unique and despite the fact that a casual visual examination of a total part population normally will not reveal commonalities, parts can be categorized into groups or families if their fundamental attributes are identified. Through the systematic classification and grouping of parts into families based on their design or production similarities, significant cost reductions can be achieved. Parts classification is a necessary activity in group technology systems and can be accomplished using one of a variety of classification and coding schemes.

The scope of group technology is broad. Since its inception, it has been associated with part family manufacturing and has been considered to affect all areas of a manufacturing company including design, process planning, manufacturing, assembly, etc. It should also be noted that group technology applies both to mass production where the approach of fixed automation (for example, transfer-line machines) is used and to small lot, discrete-parts manufacturing. In the typical manufacturing plant, the excessive setup time caused by the product mix and small lot sizes may be the most significant part of the total production time. Furthermore, plants typically have a functional layout of equipment; consequently, jobs take a nearly unpredictable path through the plant in order to reach all the necessary processing locations. Production scheduling and production control become very complicated, and actual information on the status of any particular job is nearly impossible to obtain.

Group technology alleviates the situation of mass confusion by first grouping parts into families having manufacturing similarities. In this way, different parts requiring similar machines and tooling may be processed in a sequence that increases the quantity per setup, thereby significantly reducing setup times and costs. Machines used in the production of similar part families are grouped together forming a machine group or cell (hence, the name cellular manufacturing). This layout has the effect of reducing the scope of the problems of production scheduling, production control, material handling, etc., and at the same time tends to improve the operators' morale. Problems related to tooling, for example, can be simplified through the use of fixtures common to an entire part family.

Benefits and Problems

The implementation of group technology will yield advantages in areas such as component standardization, reliability of estimates, effective machine operation, productivity, costing accuracy, customer service and order potential. At the same time, implementation of group technology can be expected to bring reductions in planning effort, paperwork, setup time, downtime, work-in-process, work movement, overall production times, finished parts stock and overall costs. There are numerous case studies in the technical literature that cite specific benefits obtained through the implementation of group technology. Representative of these benefits are reductions in the following categories:

- 52 percent in new part design
- 10 percent in number of drawings through standardization
- 30 percent in new shop drawings
- 60 percent in industrial engineering time
- 20 percent in production floor space required

- 42 percent in raw material stocks
- 69 percent in setup time
- 70 percent in throughput time
- 62 percent in work-in-process inventory
- 82 percent in overdue orders

In addition to these advantages, group technology enhances the humanization of work and improves the quality of life in a manufacturing environment. Because machines are grouped to accommodate part families, the workers are able to clearly see their contribution to the final product. It has also been found that setup changes from one part to another similar one require less skill from employees than was formerly demanded. This creates possibilities for job enlargement. Indeed, one of the major benefits of group technology is increased worker satisfaction.

As may be expected, some problems in implementing group technology have been noted. These include the following:

- Group technology requires a steady workload to assure worker satisfaction since the work-in-process is low.
- Group technology may require major changes in the organization of the production system involving such items as redesign of products, standardization and modularization of subassemblies and regrouping of equipment.
- Since group technology typically involves fewer people than machines, some of the machines will have a low utilization level.
- Group technology is particularly applicable to situations where there are a large number of small batches.
- Supervision of a manufacturing cell organized according to the principles of group technology may be more difficult than supervision of a conventional functional layout.

Classification and Coding

Classification and coding for group technology applications is a very complex problem. Although many systems have been developed throughout the world and countless efforts have been made to improve them, there is not, as yet, any universally accepted and acclaimed system.

A well-designed classification and coding system provides many benefits and facilitates group technology applications in many areas of company operations. The major benefits of a well-designed classification and coding system can be summarized as follows:

- facilitates formation of part families and machine groups
- allows quick retrieval of designs, drawings and production plans
- brings about a reduction in design duplication
- permits design rationalization and reduction of design costs
- secures reliable workpiece statistics
- facilitates accurate estimation of machine tool requirements, logical machine loadings and optimized capital expenditures
- permits rationalization of tooling setups and reductions in setup time and overall production time
- brings about rationalization and improvement in tool design
- allows for rationalization of production planning procedures and scheduling
- improves accurate cost accounting and estimation procedures
- causes better utilization of machine tools, workholding devices and manpower
- improves the effective use of NC machines

Although all departments may use a classification and coding system in one way or another, the two major users of the system are the design/engineering and manufacturing areas. Therefore, a system should be evaluated to determine whether it fulfills all the requirements and provides all the information needed by each of these two departments. Table 24-1 is representative of some of the information and data that should be included in a well-designed classification and coding system.

TABLE 24-1 Basic Information Requirements of Classification and Coding Systems

DESIGN/ENGINEERING AREA
main shape
shape element
material
rough shape and size
major dimensions
minor dimensions
tolerances
functions
assembly
drawing size, etc.
MANUFACTURING AREA
major operation
minor operation
major dimension and size ratio
rough shape and size
machine tool
workholding devices
cutting tools
lot size
setup time
production time
operation sequence
surface roughness
special treatment
inspection
assembly, etc.

While a classification system for group technology applications should be based on classes which are themselves rational, explicit and mutually exclusive, a coding system is a symbolic form of shorthand which can take a number of different forms in communicating specific information or data. There are two basic coding system structures for part classification. These are the hierarchical structure and the chain-type structure. In a *hierarchical* code, the information represented by each subsequent digit is dependent on the preceding digit, and the code number is assigned by a step-by-step examination of part characteristics as they relate to a series of coding charts. A *chain-type* structure is a fixed-digit-significance code where a certain digit value always represents the same feature. Most systems are designed with a combination of these two basic forms, although some systems use a hierarchical code for primary codes and a chain-type code for secondary codes.

Relationship of Group Technology to Numerical Control

Although both group technology and numerical control are manufacturing-related technologies that have been in existence for several decades, attention has only recently focused on their interrelationship. Many advantages of using NC machine tools have been cited, and a number of these advantages take on even greater importance in a group technology environment. Often, the combination of group technology and numerical control produces synergistic results. NC machine tools are capable of producing parts economically in smaller lot sizes than can ordinarily be justified when conventional machine tools are used. Since group technology is a manufacturing philosophy particularly applicable to small batch production, it should not be surprising that the two technologies have many things in common. These similarities, however, should not lead one to assume that they are completely compatible. It is necessary to understand the interrelationship of group technology and NC so that in situations where they are both applied, they can be combined to achieve maximum effectiveness.

The greatest potential for the application of group technology to NC machine shops is in the area of *cellular manufacturing*. This aspect, while offering more potential benefits specifically for NC shops than the other aspects of group technology, should not cause one to ignore the benefits from the other aspects discussed previously. Often overlooked is the position which a numerically controlled machine tool occupies in a manufacturing cycle and the effect that this has on the work-in-process. An NC drilling machine, for example, is commonly used for operations near the end of a manufacturing cycle and consequently is very effective in reducing work-in-process. Conversely, NC lathes are frequently the first machines in a production cycle; and since they are efficient producers of partly finished work, they can substantially increase work-in-process unless they are effectively supported by subsequent operations. Cellular manufacturing is an appropriate method for providing the dedicated support of other machines that is necessary to fully utilize a machining center.

Group technology can also make economically feasible the use of NC equipment which might otherwise be too expensive for an ordinary job shop. To a small job shop owner, the advantages of numerical control often seem outweighed by the many problems and costs of production planning and underutilization of equipment. Appropriate implementation of group technology can reduce these problems to a point where it can become economically beneficial to introduce NC equipment into the job shop.

Computer-Aided Process Planning

Process planning refers to the selection of the procedures required to convert a part design into a piece of hardware. The steps in process planning are shown in figure 24-2. They include raw material selection, development of a sequence of manufacturing operations, selection of fixtures, development of tooling and tool configuration, development of cut sequence and NC program, and selection of detailed machining technology, such as feed, speed and tool-change frequency. Typically, the end product of process planning is a set of detailed operation instructions and NC tapes which are used by the machinist in making the part. Process planning may be performed by more than one person. Typically, these people are referred to as planners, methods engineers, manufacturing engineers, process planners, value engineers, or NC programmers.

Process planning is one of the active areas of CAD/CAM implementation. Currently, the computer is being utilized to facilitate certain steps in the process planning sequence. These are: (1) the development of operation sequences, (2) the selection of tooling and the preparation of NC programs and graphical operator instructions, and (3) the selection of machining conditions. In each of these areas, research in the U. S. and abroad is bringing about substantial improvements.

Development of Operation Sequences

The sequence of machining and nonmachining operations that are required to produce a part are generally chosen on the basis of past experience with similar parts. The planner uses his memory or a stored document to produce a sequence that is typically used for the particular part type that he is planning. Along with the standard sequence, the processing time and work station associated with the operation may be retrieved. The standard sequence is then altered to fit the specific part being planned. Additional operations may be required, work stations or planned time may be altered, or operations may be deleted. This approach is referred to as the *variant* method of process planning. The final plan is a variation of a standard plan.

The variant approach lends itself to computerization with the incorporation of a group technology classification and coding scheme. First, all parts which have been processed previously are coded using a group technology scheme. Second, the parts are divided into part families, each part family requiring a unique sequence of operations. Standard sequences are stored on the computer for each part family. When a new part arrives for planning, the group technology code for the new part is used to retrieve the standard operation sequence for the appropriate part family. Finally, an interactive editor is used to alter the standard sequence to fit the part, and the final sequence is stored in the computer data base by the part number to which it applies. The variant approach is currently exemplified by the CAM-I CAPP system (Computer Aided Manufacturing-International, Inc., Automated Process Planning).

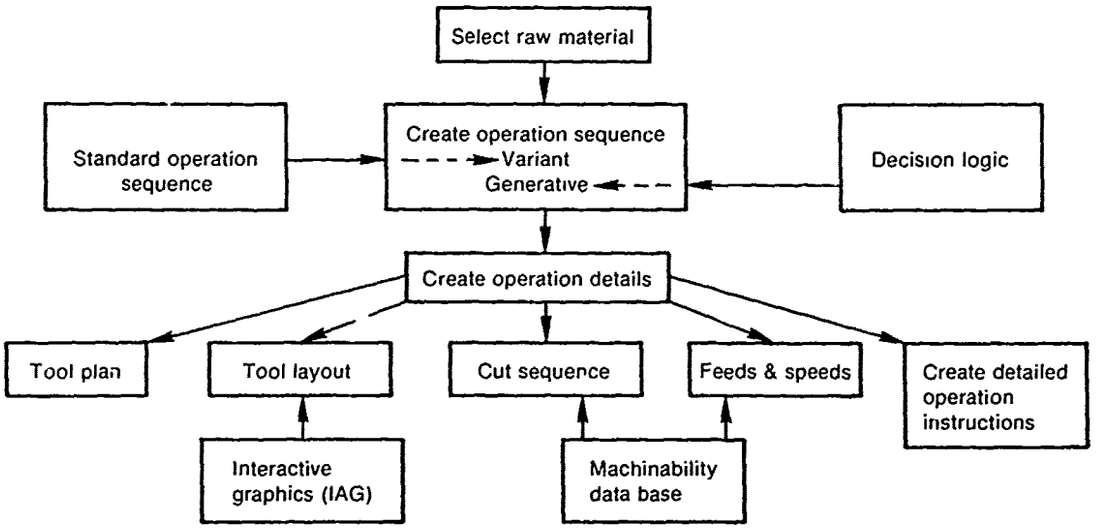


Figure 24–2 Process planning overview.

Another approach to developing a sequence of operations is termed the *generative* approach. In this approach, the parts are again broken into part families, but a rigorous analysis is made for each part family to determine what features of the part require which operations. This results in the process planning logic for the part family, which is stored as a decision model. When a new part requires planning, it first must be analyzed to determine what features that are incorporated in the decision logic are present on the part. The decision model is retrieved and an operation sequence is generated by processing the decision model with the part features. Essentially, the computer executes the thought process of the planner.

Interactive Graphics in Process Planning

An important computerized tool that is playing an increasing role in the task of the process planner is interactive graphics (IAG). There are about a dozen IAG systems that are commercially available which can be used by a planner to develop tool layouts, assist in NC programming and compose graphical operation instructions. This graphical composition and analysis of tool layout and NC geometry provides an extremely powerful verification capability which previously required hours of time-consuming drafting and analysis. Now, a tooling layout can be composed and driven by an NC tape to simulate the cutting process in a matter of minutes. Figure 24–3 shows a time exposure of an IAG display of a turret layout driven through its NC cutter path.

Selection of Machining Conditions

Often the specific machining conditions, such as tool material, feed, speed and coolant are not specified in a process plan. The machinist is left to make these decisions when the part arrives for machining. This is changing, however, because both the cost of sophisticated NC equipment and the complexity of available tool materials and grades are increasing. The computer is being used to select the appropriate grade of cutting tool and to evaluate the feeds and speeds to reduce cost and machining time. In some NC programming systems, such as ADAPT and GETURN, these machining conditions are automatically specified in the NC program. As an alternative, computerized files of machining data are being developed which can be used to evaluate the cost, time, cutting forces, surface roughness, and chatter that result over a range of feeds and speeds. This analysis enables an NC programmer or planner to specify cutting conditions which meet the manufacturing requirements of the part while attempting to minimize cost and production time.

It is apparent that process planning is enjoying the benefits of computer automation. The planner can look forward to more and more automated assistance through interactive graphics, NC programming, group technology and manufacturing data bases. The computer is also moving the process planning function from an experience-based procedure to a data-based procedure. The experience of manufacturing engineers and planners is being put into the computer, and this stored data is providing the decision logic to support existing and future process planning systems.

Manufacturing Data Bases

At the heart of computer-assisted process planning, group technology or CAD systems is the manufacturing data base. The manufacturing data base provides the ability to store the vast amounts of data that are necessary to support the engineering analyses performed by these systems in formats that can be easily and quickly searched to retrieve individual data elements. Without this ability, engineering analyses performed by process planning, group technology or CAD systems would be extremely slow or impossible.

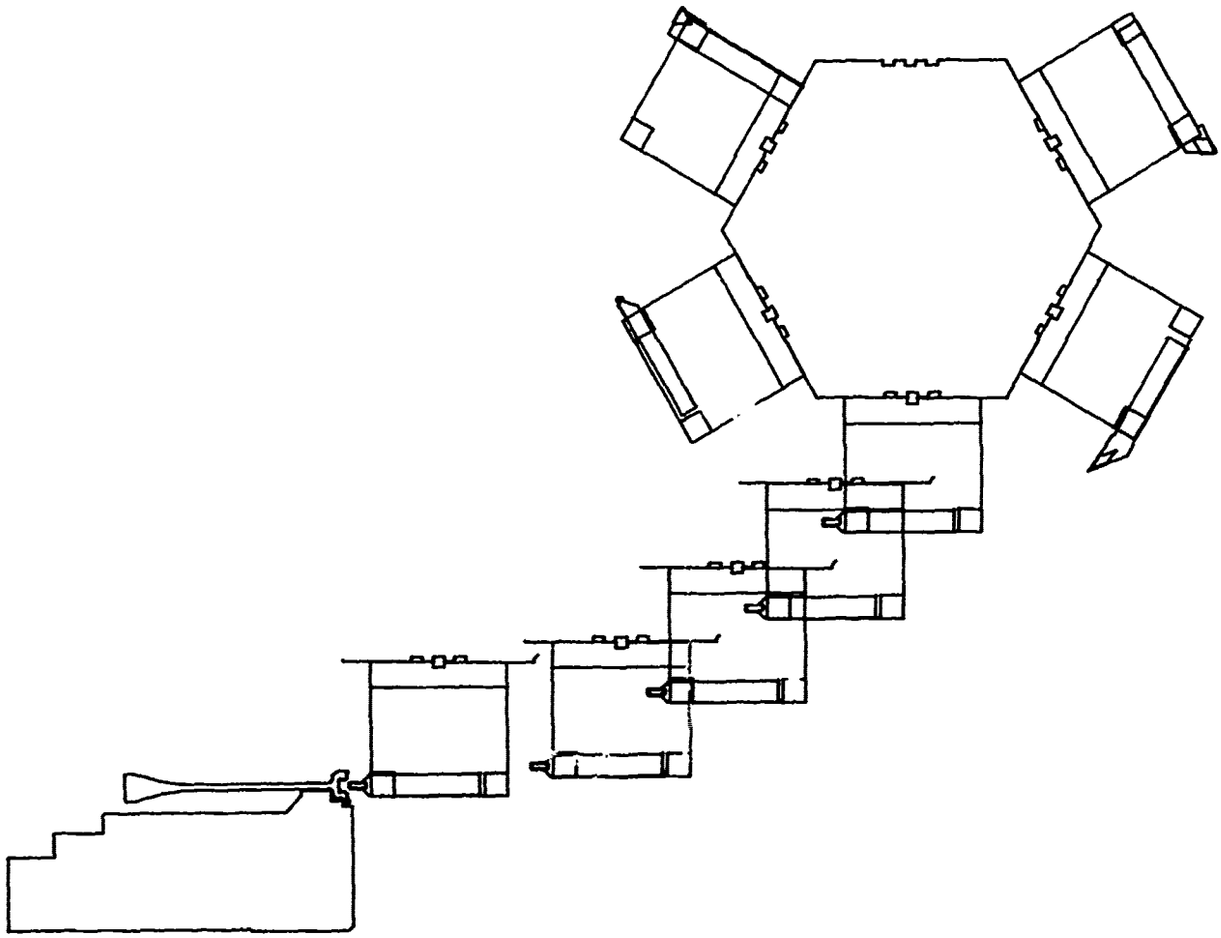


Figure 24–3 Interactive graphics display of a tooling layout.

The growth of computer data bases in engineering analysis has been relatively recent. The first applications of data bases were inventory control, personnel/payroll and customer order processing. Early inventory control systems were primarily punched-card systems. Each item in inventory had a corresponding computer card. When the item was removed, the card was removed and read by the computer. The system generally operated in batch mode and generally provided only daily summaries of inventory status. Eventually, inventory systems expanded to include other tasks such as shipping/receiving, billing, customer order processing and other accounting functions. Very quickly, the demand for computer information processing systems grew in all fields, including manufacturing. Two major computer developments accelerated computer information system growth: time-sharing, real-time computers and the development of data base managers.

The time-sharing computer allows multiple users to use the computer simultaneously from remote locations. Cathode ray tubes (CRT) are used to communicate with the computer, eliminating much of the hard-copy input (cards) and output. Users are able to obtain immediate answers to their questions rather than waiting hours or days until their job is processed. A data base manager (DBM) is software which efficiently stores and retrieves data using specialized cataloging methods. DBM's allow the data to be structured and cross-referenced in many ways that tremendously increase the speed of data retrieval. Numerous DBM's and strategies for data structuring are available. Manufacturing data base systems incorporate the DBM to perform the routine storage, retrieval, updating and searching tasks. Figure 24–4 shows how a typical manufacturing data base might be structured. The structuring of the data base and the processing of the retrieved data are areas

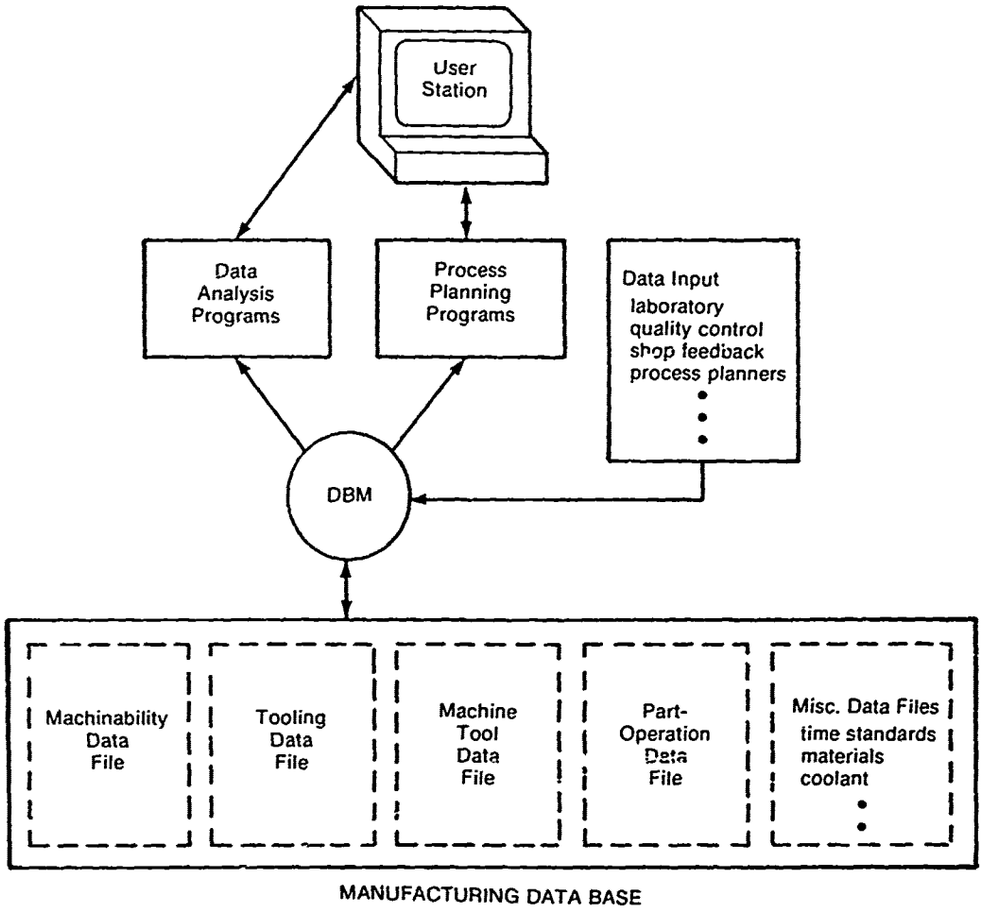


Figure 24–4 Typical manufacturing data base structure.

where new manufacturing data base developments are forthcoming.

Manufacturing data bases consist of many types of data files, such as the following: geometrical description of part design, workpiece material properties, tooling, machine tool, raw material geometrical description, part/operation description and machinability data. All of these files are related to each other in varying degrees, and, depending on the engineering analysis performed, one or several of the data files may be used. All of the files except the machinability data file simply store and retrieve the description of the major characteristics of each data item. For example, the tooling file may store the following data for a given cutting tool: company code number, tool material, size and shape, rake, clearance and/or helix angles, quantity in stock, inventory location, regrinding information, price, vendor and recommended applications. The machine tool, workpiece material and part/operation files would be similar, but with different data items (for example, the machine tool file would store horsepower, table size, available speeds and feeds, etc.). The geometrical description files store in a special coded form the size and shape of a part. Using Cartesian coordinates and codes for holes, fillets, cylinders, etc., the part is completely described. The coded sequences of numbers are stored and used for interactive graphics and computer drafting routines.

The machinability data file is unique in many respects. Early machinability data files operated in a fashion similar to the other data files; that is, a series of recommended cutting speeds and feed rates were stored for numerous combinations of work material, tool material, cutting fluid and cut size. The structure of the data file was similar to a machinability data handbook. Given the required inputs (tool, cut size, material), the computer would look up the recommended speed and feed. The advantages over a printed handbook were that the recommended cutting conditions could be easily updated, more combinations of tools and cut sizes (depths of cut) could be entered, and automatic interpolation between recommended values could be incorporated. The major disadvantage was that significant engineering analysis was required not only to set up the original recommended cutting speeds and feeds but also to update and maintain current recommendations. The lack of adequate data base maintenance is the most common

reason given for the failure of the early machinability data bases.

More recent machinability data base systems use a different approach. Rather than storing recommended cutting conditions and simply retrieving them, the new systems actually perform the engineering analysis necessary to determine the recommended cutting conditions. The recommendations are computed when they are needed and use a base set of raw machinability data. The raw machinability data may be machinability test results, shop-adjusted speeds and feeds, and/or published machinability data. The data may be tool life, cutting forces, surface roughness, horsepower or tool breakage data. The data bank comprises the most basic data elements; no preprocessing of the data is required. The engineering logic used to generate speeds and feeds is programmed into the computer system. Rather than the engineer performing his analysis every time new data become available, he establishes the procedure once and lets the computer perform the analysis when needed. The advantages are that the maintenance is minimal, that the engineer can concentrate his effort on the procedure or logic to use rather than on many repetitive analyses, and that more sophisticated analyses can be performed which are customized to the individual situation encountered. As a result, cutting speeds and feed rates are recommended which are closer to the optimum and may result in higher productivity.

COMPUTERS IN MANUFACTURING CONTROL

DNC and CNC

The primary advantage of using computers for NC operations is better control of the supporting functions which include parts program generation, data transmission, storage and fit techniques, and possibly the elimination of paper tapes and associated equipment. In addition, computer-assisted NC does indeed offer significant advantages with respect to control functions and can be justified as a direct replacement for conventional NC.

There are two different concepts of computer control of machine tools: CNC (computerized numerical control) and DNC (direct numerical control).

With CNC, the computer—usually a general purpose minicomputer—is dedicated to the control of only one machine. This minicomputer receives all pertinent machine information, calculates or performs logic functions to update machine instructions, then sends the instructions to the machine. Figure 24-5 shows a block diagram of a CNC system having both the central processing unit (CPU) which takes over the data handling and the control hardware which manipulates the NC machine tool. In addition, the CPU can perform data processing similar to that performed by a tape preparation system.

Conversely, DNC utilizes a central computer, multiplexed (time shared) to control a number of machines simultaneously (see figure 24-6). The main function of the computer is to police each machine and to make certain that it is supplied with sufficient data. DNC systems are usually open loop, which means that the computer updates the data when requested by each machine but does not follow up during machine operation.

Although CNC costs about the same as NC for the same level of sophistication, CNC has some advantages. The flexibility of CNC permits ready addition or reconfiguration of functions by simple software modifications rather than by the physical modifications required for hard-wired NC. Programming, including program modification, is simplified with CNC. CNC also permits the use of error message displays, the logging of management data and the use of diagnostic programs for detecting malfunctions.

DNC offers several operating advantages. First, the tape reader, which usually is the most downtime-prone component of a machine control unit, is bypassed. Second, a program in computer storage is much easier to access for operational use, for revision or editing, or for quick and easy interaction between programmer and machine tool. Third, the same computer that directs the operation of a machine tool can also be used for auxiliary purposes such as downtime recording, performance tabulation, real-time machine status and other operational items of interest to management. Gathered information may either be kept in the controlling computer's memory or it may be transmitted to some other type of data gathering unit where it may be organized for use by the manufacturing management staff.

An advanced-design DNC unit could also be used to sense operating conditions and even to make modifications to programmed instructions based upon the gathered data. With all operational instructions coded in terms of unseen computer software, DNC does require programmers and supervisors who have a very clear and thorough understanding of production operations in order to exercise full and optimum control. DNC systems can be extremely effective when combined with first-rate systems know-how, but the initial cost will probably be high and the support must always be of the highest caliber.

Even though CNC (by definition) has its own dedicated computer, it can also communicate readily with other computers as part of a DNC system. As production DNC systems develop, CNC machine tools can be readily integrated. This integration has greatly reduced the dependence on a single computer. In the case of a failure in the DNC computer, the CNC systems can continue to operate the machine tools satisfactorily.

Adaptive Control

Adaptive control (AC) is a process control method that uses sensors for real-time measurement of process variables and calculates and adjusts control parameters to achieve near-optimum process performance. Adaptive control of the metalcutting process was introduced in the early 1960's and has since demonstrated that its use can increase productivity and reduce costs. While some machine tools can be purchased today with AC as an option, it is more common to retrofit AC units onto existing machine tools. The metalcutting applications of AC often cite increases in metal removal rate on the order of 50 percent; yet, AC has had a broader impact on the metalcutting field than the

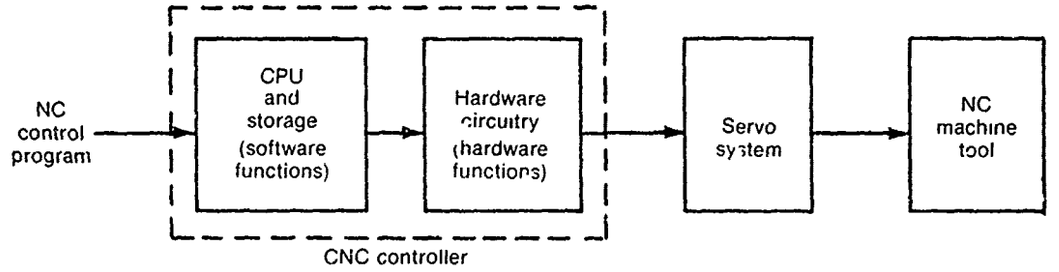


Figure 24–5 Typical CNC system diagram.

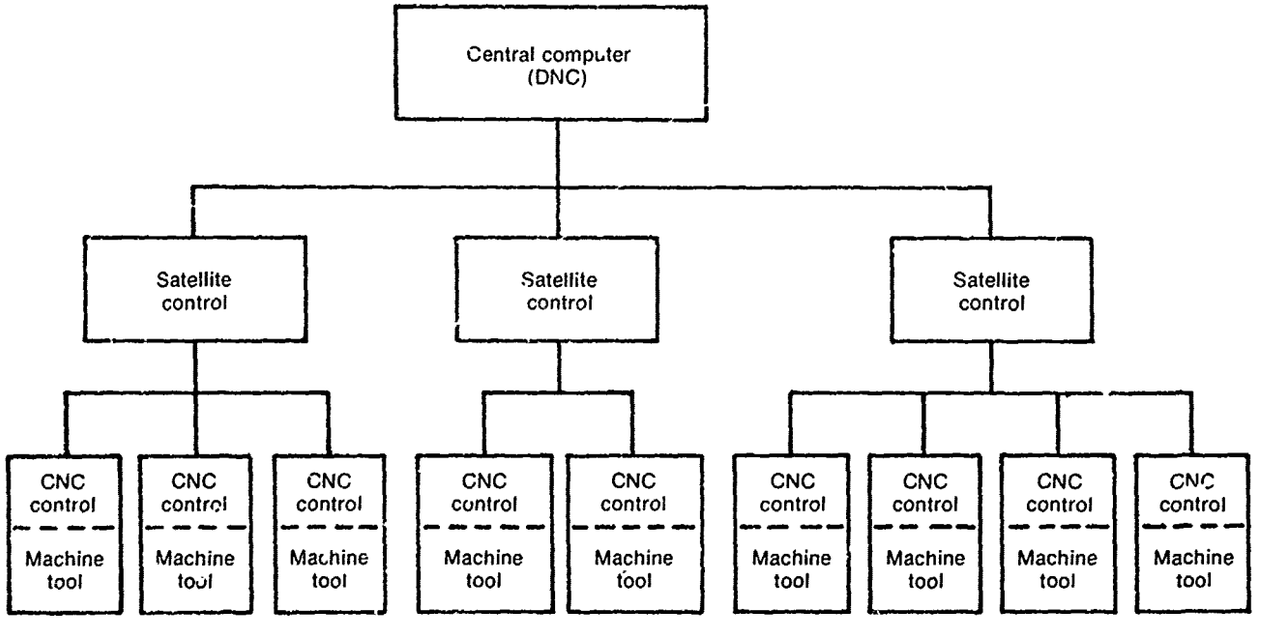


Figure 24–6 DNC system configuration with satellite and CNC computer controls.

simple optimization of machining rates. Since it requires an understanding of the total machining operation as a system, AC has fostered in-depth studies of the system components and their interactions. Metalcutting applications of AC are still rather limited in number, primarily because system costs are high and it is difficult to obtain sensors suitable for a process affected by many difficult-to-predict process parameters.

For conventional and numerical control, machining speed and feed data such as that contained in this handbook as well as tool life data from either curves or computerized data banks are extremely helpful for selecting machining parameters. These data, however, are not completely adequate for AC. In order to optimize, demands are now being made for data on tool forces developed during machining and on the effect on these forces of variables such as cutter design, tooth design and geometry, type of work material and hardness, and extent of tool wear. With these data, reasonable constraints can be selected to maximize feeds and speeds without the risk of cutter breakage The advantages and limitations of AC are listed in table 24-2.

TABLE 24-2 Advantages and Limitations of AC Systems

ADVANTAGES
Increased productivity
Reduced cost of production
Improved product quality
Lower scrap rates
Higher machine utilization
Protection of machine, tool, workpiece from damage
Reduced dependence on operator skill
Improved and simplified programming
LIMITATIONS
High cost and complexity
Poor system reliability
Existing systems do not guarantee maximum metal removal rates
Inadequacy of data banks
Variable cycle times
Increased maintenance costs
Expensive and unreliable sensors for key AC process performance parameters

The various types of AC systems can be classified as follows, recognizing that there is no simple definition of AC

Feedback AC In these systems, some process parameter, such as motor current or horsepower, is predetermined to be optimal The machine tool system has the capability of monitoring the level of the process parameter and compensating for differences in its level by adjusting the cutting speed or feed rate

Constraint AC In these systems, the cutting speed and/or feed is maximized within specified limits for the machine or cutting tool. Common constraints include maximum torque, force, or horsepower. These are the most prevalent systems currently in use since they are relatively simple and inexpensive. Most are based only on the adjustment of the feed to reach to optimum condition within the constraint region.

Optimization AC In these systems, an index of performance or a figure of merit (usually based on some economic function involving minimum cost or maximum production rate) is established. During operation, the process performance is compared with the index or merit figure. The system has the capability of deciding how and when to use the results of the comparison to improve the performance through implementation of a change in operating parameters. Most systems of this type are still laboratory systems used for research. Development of indices of performance that are realistic yet simple and of sensors that are reliable and inexpensive are the two necessary steps toward production usage of these systems.

The area of sensor development for AC systems is appropriately receiving much attention. The R&D efforts are focusing on cost reduction and on improved sensor reliability. The state of the art of sensor technology is such that several of the key metalcutting parameters including tool wear and surface quality cannot be easily or accurately monitored in the production environment.

It appears that interest in AC as applied to material removal was first generated by development work on rather complex systems However, it appears that industry will continue to initiate more extensive use of AC with relatively simple systems designed to achieve cost savings without using highly expensive or delicate sensor and control systems. Interest is currently being shown in sensors and controls which can easily be adapted to existing machine tools. As further economic advantages are recognized, more complex AC systems will find application, especially as computer-aided manufacturing becomes more widely used.

SECTION 25

MACHINING STANDARDS

25.1 Machining Standards by Subject 25–3
25.2 Alphabetical List of Machining Standards 25–9
25.3 Sources of Machining Standards 25–23

PRECEDING PAGE BLANK-NOT FILMED

Abrasives, Abrasive Wheels and Belts:
- GGG-W-290B
- GGG-W-301B
- MIL-W-16102C(1)
- MIL-W-17929B(1)

Abrasive Grains,
- ANSI B74.4-1977
- ANSI B74 5-1964 (R1976)
- ANSI B74.6-1964 (R1976)
- ANSI B74.8-1977

Diamond,
- ANSI B74.1-1966
- ANSI B74.3-1974
- ANSI B74 16-1971 (R1976)
- ANSI B74.17-1973 (R1978)
- DWMI 101
- DMWI 102
- DWMI 103
- DWMI 104
- DWMI 105
- DWMI 106

Dressing,
- ANSI B67.1-1975

Identification Codes and Dimensions,
- ANSI B74.1-1966
- ANSI B74.2-1974
- ANSI B74.3-1974
- ANSI B74.9-1970 (R1976)
- ANSI B74.10-1977
- ANSI B74.11-1967 (R1978)
- ANSI B74.12-1977
- ANSI B74.13-1977
- ANSI B74.18-1977
- ISO 525-1975
- ISO/R 603-1967
- ISO 1117-1975
- ISO 1929-1974
- ISO 2933-1974
- ISO 2976-1973
- ISO 3919-1977
- ISO 5429-1977

Mounting,
- ANSI B5.35-1969 (R1975)

Safety,
- ANSI B7.1-1978

Computer Software:
- ANSI X3.37-1977

Cutting Fluids:
- ANSI Z11.142-1964 (R1974)
- ASTM D88-56 (1973)
- ASTM D92-72 (1977)
- ASTM D94-71 (1976)
- ASTM D129-64 (1973)
- ASTM D130-75
- ASTM D156-64 (1977)
- ASTM D287-67 (1977)
- ASTM D445-74
- ASTM D808-63 (1976)
- ASTM D892-74
- ASTM D1479-64 (1973)
- ASTM D1662-69 (1974)
- ASTM D2670-67 (1977)
- MIL-C-46113B
- MIL-C-46149
- VV-C-846A(1)
- VV-C-850A(1)

Cutting Tools:
- ISO 2584-1972
- ISO 2585-1972
- ISO 3337-1975
- ISO 3859-1977
- ISO 3940-1977
- ISO 5421-1977

Bur Blanks,
- ANSI B94 13-1976

Carbide Tipped Turning Tools,
- ISO 242-1975
- ISO 243-1975
- ISO 504-1975
- ISO 514-1975

Counterbores,
- ISO 4206-1977
- ISO 4207-1977
- MIL-C-936

Countersinks,
- ISO 3293-1975
- ISO 3294-1975
- ISO 4204-1977
- ISO 4205-1977

Cut-off Blades,
- ANSI B94.3-1965 (R1972)

Designations,
- ISO 513-1975

Drills,
- ANSI B94.12-1977
- ANSI B94.49-1975
- ANSI B104.1-1964
- ISO 235/2-1972
- ISO 2306-1972
- ISO 3314-1975
- NAS 932
- NAS 937
- NAS 965
- See also **Cutting Tools:** Twist Drills

End Mills,
- ANSI B94.19-1977
- ANSI B94.20-1977
- ISO 1641/1-1978
- ISO 1641/2-1978
- ISO 1641/3-1978
- ISO 2324-1972
- MS-15704B
- MS-15705A
- MS-15706A
- MS-15707B
- MS-15708B
- MS-15709B
- MS-15710B
- MS-15711B
- MS-15713A
- MS-15714A
- MS-15715A
- MS-15716B
- NAS 986

25.1 Machining Standards by Subject

Files,
GGG-F-00340(2)
Forming Tools,
ANSI B94.32-1954 (R1971)
Geometry,
ISO 3002/1-1977
Hobs,
AGMA 120.01-1975
ANSI B94.7-1966 (R1972)
Honing Stones,
ISO 3920-1976
ISO 3921-1976
Inserts,
ANSI B94.4-1976
ANSI B94 24-1976
ANSI B94.25-1975
ISO 883-1976
ISO 1832-1977
ISO 3364-1977
ISO 3365/1-1977
Knurling,
ANSI B94.6-1966 (R1972)
Milling Cutters,
ANSI B94.8-1967 (R1972)
ANSI B94.19-1977
GGG-C-755E
ISO 240-1975
ISO 532-1974
ISO 2587-1972
ISO 2780-1973
ISO 2940/1-1974
ISO 2940/2-1974
ISO 3365/1-1977
ISO 3855-1977
ISO 3860-1976
MS-15687C
MS-15688B
MS-15689A
MS-15690B
MS-15691A
MS-15693A
MS-15694B
MS-15695B
MS-15696B
MS-15698B
MS-15699B
MS-15700B
MS-15701A
MS-15702B
MS-15717B
MS-15718B
MS-15719B
See also **Cutting Tools:** End Mills
Reamers,
ANSI B94.2-1977
ANSI B94.20-1977
ISO 236/1-1976
ISO 236/2-1976
ISO 521-1975
ISO 522-1975
ISO 2250-1972
ISO 3465-1975
ISO 3466-1975
ISO 3467-1975
Saw Blades,
ANSI B94.42-1972 (R1978)
ANSI B94.51-1976 (1977)
ANSI B94.52-1977
ANSI B122.1-1970
GGG-B-421C
GGG-B-431A(1)
GGG-S-66B(SH)
ISO 2296-1972
ISO 2336-1972
ISO 2924-1973
ISO 4875/1-1978
MIL-H-938
MS-17008
MS-17010
MS-17011
MS-17012
Shaper Cutters,
ANSI B94.21-1968 (R1974)
Single-Point Tools,
ANSI B94.5-1974
ANSI B94.10-1967 (R1972)
ANSI B94.37-1972
ANSI B94.50-1975
ISO 3286-1976
Taps,
ANSI B94.1-1977
ANSI B94.9-1971
ISO 529-1975
ISO 2283-1972
ISO 2857-1973
Twist Drills,
ANSI B94.11-1967 (R1972)
ANSI B94.20-1977
GGG-D-751C(2)
ISO 235/1-1975
ISO 494-1975
ISO 3291-1975
ISO 3292-1975
ISO 3438-1975
ISO 3439-1975
NAS 907

Grinding of Steel:
MIL-STD-866A
MIL-STD-1571

Industrial Engineering:
ANSI Z94.10-1972
ANSI Z94.12-1972
MIL-STD-1567

Inspection Machines:
NAS 971

Limits, Fits and Tolerances:
ANSI Y14.5-1973
Cylindrical Parts,
ANSI B4.1-1967 (R1974)
Metric,
ANSI B4.2-1978
ANSI B4.3-1978

Machine Tool Components, Accessories and Attachments:
- Boring Machines,
  - MIL-STD-950A
- Broaching Machines,
  - MIL-STD-945A
- Bushings,
  - ANSI B94.33-1974
- Chucks,
  - ANSI B5.8-1972 (R1979)
  - GGG-C-350B
  - ISO 3089-1974
  - ISO 3442-1975
  - MIL-C-45576
  - MIL-C-45833C
- Clamps, Vises and Wedges,
  - GGG-V191D
  - GGG-V-433A
  - GGG-W-220B(1)
- Drilling and Tapping Machines,
  - MIL-STD-932
  - OO-M-340B
- Drivers,
  - ANSI B94.35-1972
- Electrical and Ultrasonic Erosion Machines,
  - MIL-STD-955A
- Gear Cutting and Finishing Machines,
  - MIL-STD-958A
- Grinding Machines,
  - MIL-STD-948A
  - OO-G-573A
  - OO-M-340B
- Holders, Tool Insert and Bit,
  - ANSI B94.26-1969
  - ANSI B94.45-1973
  - ANSI B94.46-1973
  - ANSI B94.47-1973
  - ANSI B94.48-1976
  - MIL-H-4081B(2)
  - NAS 970
  - OO-C-00845
  - OO-C-851A(1)
  - OO-H-581A
- Lapping Plate,
  - GGG-P-446A
- Lathes,
  - MIL-STD-931
  - OO-D-565A
- Machining Centers,
  - MIL-STD-938A
- Milling Machines,
  - MIL-STD-956A
  - OO-M-340B
- Miscellaneous Machine Tools,
  - MIL-STD-957A
- Pilots,
  - ISO 4208-1977
- Planers and Shapers,
  - MIL-STD-959A
- Quill Flanges,
  - ANSI B5.41-1968 (R1973)
- Saws and Filing Machines,
  - MIL-STD-941A
- Socket,
  - OO-S-550A
- Spindle Noses,
  - ANSI B5.9-1967 (R1972)
  - ANSI B5.11-1964 (R1973)
  - ANSI B5.18-1972
  - ANSI B5.40-1977
- Step Blocks,
  - GGG-B-461A
- Tables,
  - MIL-T-80218
- Tapers,
  - ANSI B5.10-1963 (R1972)
- T-Slots,
  - ANSI B5.1-1975

Machine Tools:
- ISO 229-1973
- ISO/R230-1961
- NAS 938
- Accuracy,
  - ANSI B5.16-1952 (R1979)
  - ISO 1701-1974
  - ISO 1708-1975
  - ISO 1984-197A
  - ISO 1985-1974
  - ISO 1986-1974
  - ISO 2407-1973
  - ISO 2423-1974
  - ISO 2433-1973
  - ISO 2772/1-1973
  - ISO 2772/2-1974
  - ISO 2773/1-1973
  - ISO 2773/2-1973
  - ISO 3070/0-1975
  - ISO 3070/1-1975
  - ISO 3070/2-1978
  - ISO 3190-1975
  - ISO 3655/0-1976
  - ISO 3655/1-1976
  - ISO 3686-1976
  - ISO 4703-1977
  - NAS 979
  - NMTBA (1968)
  - See also standards for specific machine tools
- Belt Grinders,
  - MIL-G-80176A
- Boring Machines,
  - ISO 3070/0-1975
  - ISO 3070/1-1975
  - ISO 3070/2-1978
  - ISO 3686-1976
  - MIL-B-4554B
  - MIL-B-9925C
  - MIL-B-80012B
  - NAS 910
- *Numerically Controlled,*
  - MIL-B-80004B
  - MIL-B-80094B
  - MIL-B-80202(1)
  - MIL-B-80210A
  - MIL-B-80248(1)
  - NAS 954

NAS 963
NAS 978
Broaching Machines.
MIL-B-80203
Buffing-grinding-polishing Machines.
OO-B-791(2)
W-G-656D(3)
Center Hole Grinders.
MIL-G-80179
Computerized Numerical Control.
NAS 995
Cutoff Machines.
MIL-C-80021A(1)
MIL-C-80071A
Cylindrical Grinders.
ANSI B5.33-1970
ANSI B5.37-1970
ANSI B5.42-1970
ISO 2407-1973
ISO 2433-1973
MIL-G-23368B(1)
MIL-G-23823C
MIL-G-80048B(1)
Direct Numerical Control.
NAS 993
Disc Grinders.
MIL-G-80126A
Drilling Machines.
ISO 2423-1974
ISO 2772/1-1973
ISO 2772/2-1974
ISO 2773/1-1973
ISO 2773/2-1973
ISO 3190-1975
ISO 3686-1976
MIL-B-4554B
MIL-D-3141B
MIL-D-17674D
MIL-D-18072C
MIL-D-80010C(1)
MIL-D-80076B
MIL-D-80150A
MIL-D-80193A
MIL-D-80225
NAS 910
OO-D-696A
Numerically Controlled.
MIL-B-80094B
MIL-D-80077B
MIL-D-80078B
MIL-D-80084A
NAS 948
NAS 954
NAS 960
NAS 978
Electrochemical Machines.
MIL-E-80100A
MIL-E-80238
Electrical Discharge Machines.
MIL-E-80023B
MIL-E-80130A
MIL-E-80140B
MIL-E-80157A
MIL-E-80158A
Electrolytic Grinders.
MIL-E-80022A
Filing Machines.
MIL-F-12490B
MIL-F-23808
Gear Hobbing Machines.
MIL-G-80194
MIL-G-80195
MIL-G-80196
Grinding Machines.
OO-G-00661B(2)
OO-G-669F
See also under specific types
Honing Machines.
MIL-H-80003B
MIL-H-80009B
MIL-H-80216
Internal Grinders.
MIL-G-80066B
MIL-G-80073B
MIL-G-80180A
MIL-G-80228
Jig Grinders.
MIL-G-23681B
Keyseating Machine.
MIL-K-80221
Lapping Machines.
MIL-L-80005A
MIL-L-80199
Lathes.
ISO 1708-1975
ISO 3655/0-1976
ISO 3655/1-1976
MIL-B-80012B
MIL-L-4370B
MIL-L-4533D
MIL-L-11285B
MIL-L-13896D(2)
MIL-L-17966D
MIL-L-19368B
MIL-L-23225B
MIL-L-23251B(2)
MIL-L-23257B(1)
MIL-L-23400B(1)
MIL-L-45100B(1)
MIL-L-45943
MIL-L-45958
MIL-L-80006B
MIL-L-80007B
MIL-L-80018A
MIL-L-80032B
MIL-L-80061A
MIL-L-80175A
NAS 931
OO-L-125C(1)
Numerically Controlled,
MIL-B-80202(1)
MIL-B-80240(1)
MIL-L-80053B
MIL-L-80123A
MIL-L-80219A
MIL-L-80245(1)
NAS 966

Lubrication.
ISO/TR 3498-1974
ISO 5169-1977
ISO 5170-1977
Machining Centers.
MIL-M-80169A
MIL-M-80182(1)
MIL-M-80255
Metric Units.
ANSI B5.51M-1979
Milling Machines.
ANSI B5.45-1972
ISO 1701-1974
ISO 1984-1974
ISO 3070/0-1975
ISO 3070/1-1975
ISO 3070/2-1978
MIL-B-4554B
MIL-M-13934D
MIL-M-23589B
MIL-M-23855B
MIL-M-45577A
MIL-M-80016B
MIL-M-80033B
MIL-M-80044A
MIL-M-80051A(2)
MIL-M-80058A(1)
MIL-M-80059A(1)
MIL-M-80063A(1)
MIL-M-80064A
MIL-M-80097A
MIL-M-80099A
MIL-M-80127A
MIL-M-80129A
MIL-M-80155A
MIL-M-80177A
MIL-M-80206A
MIL-M-80213A
MIL-M-80215
NAS 909
NAS 910
NAS 914
NAS 929
NAS 936
OO-M-59C
Adaptive Control.
NAS 994
Numerically Controlled.
MIL-B-80004B
MIL-B-80094B
MIL-M-80168A
MIL-M-80184A
MIL-M-80204A
MIL-M-80208A
MIL-M-80209A
MIL-M-80212(1)
NAS 911
NAS 913
NAS 954
NAS 977
NAS 978
NAS 984
Multi-Purpose Machines.
MIL-M-80096B
MIL-M-80139A
MIL-M-80142A
Pipe Cutting Machines.
MIL-C-45044
Planers or Shapers.
MIL-P-80136A
MIL-S-19240A(1)
MIL-D-23375B
MIL-S-23800A(1)
MIL-S-23910A(2)
MIL-S-80001A
Plasma or Flame Cutting Machines.
MIL-C-80036B
MIL-C-80090B
Plunge Grinders.
MIL-G-80143A
Retoothing Machine.
MIL-R-19169B
Safety.
ANSI B11.6-1975
ANSI B11.8-1974
ANSI B11.9-1975
ANSI B11.13-1975
Saws.
GGG-S-66B(SH)
MIL-S-13875E
MIL-S-23807
MIL-S-23847B(1)
MIL-S-24034B
MIL-S-24035C
MIL-S-24036B
MIL-S-26789B(1)
MIL-S-45814C
MIL-S-45957
MIL-S-80201A(1)
OO-S-240E
Screw Machines.
MIL-S-23378B
Surface Grinders.
ANSI B5.32-1977
ANSI B5.32.1-1977
ANSI B5.44-1971
ISO 1985-1974
ISO 1986-1974
ISO 4703-1977
MIL-G-80088B
MIL-G-80125A
MIL-G-80145A
MIL-G-80163A
MIL-G-80239
Thread Grinders.
MIL-G-80162A
Threading Machines.
MIL-T-80166(2)
OO-T-290C
Tool and Cutter Grinders.
MIL-G-4515B
MIL-G-19120B
MIL-G-23900C
MIL-G-45072E
MIL-G-80025A
MIL-G-80065B
MIL-G-80189

NAS 973
NAS 998
OO-G-692C(1)
Utilization.
NMTBA (1975)

Machining Tests and Standards:
ANSI B94.34-1946 (R1971)
ANSI B94.36-1956 (R1971)
ASTM D1666-64 (1976)
ASTM E618-77T
ISC 3685-1977
MIL-STD-1242
NAS 979

Materials:
Carbides.
ANSI H9.7-1973
ANSI H9.10-1973
ANSI H9.24-1973
ANSI H9.26-1969 (R1974)
ASTM B276-54 (1972)
ASTM B294-76
ASTM B311-58 (1972)
ASTM B390-64 (1976)
ASTM B406-76
ASTM B421-76
ASTM B437-67 (1973)
ASTM B485-76
ASTM B611-76
for Tools. Fixtures and Gages.
ANSI B52.1-1962
Tool Steel.
ASTM A597-75
ASTM A600-76
ASTM E352-76a

Numerical Control:
ANSI C85.1-1963
ANSI X8.1-1968
ANSI X8.2-1968
ANSI X8.3-1968
EIA Automation Bulletin No. 3-C
EIA Automation Bulletin No. 4
EIA RS-227A
EIA RS-244B
EIA RS-267A
EIA RS-274C
EIA RS-281A
EIA RS-358A
EIA RS-408
EIA RS-431
EIA RS-447
NAS 938
NAS 943
NAS 953
NAS 955
NAS 968
NAS 969
See also under specific machine tools

Peening:
Glass Bead.
ANSI/SAE J1173-1977
MIL-STD-852
Shot.
MIL-S-13165B(1)

Plasma, Oxygen, Air and Electron Beam Cutting:
AWS A6.3-69
AWS C4.1-77
AWS C5.2-73
AWS C5.3-74
AWS F2.1-78

Safety:
ANSI Z43.1-1966
ANSI Z49.1-1973

Surface Technology:
AGMA 118.01-1973
ANSI B46.1-1978
ANSI Y14.36-1978
ISO/R 468-1966
ISO 1302-1974
ISO 1878-1974
ISO 1879-1974
ISO 1880-1979
ISO 2632/1-1975
ISO 2632/2-1977
ISO 3274-1975

DESIGNATION	TITLE
AGMA 118.01-1973	Information Sheet—Gear Tooth Surface Texture for Aerospace Gearing (Surface Roughness, Waviness, Form and Lay)
AGMA 120.01-1975	Fine- and Coarse-Pitch Hobs
ANSI B4.1-1967 (R1974)	Preferred Limits and Fits for Cylindrical Parts
ANSI B4.2-1978	Preferred Metric Limits and Fits
ANSI B4.3-1978	Tolerance for Metric Dimensioned Products, General
ANSI B5.1-1975	T-Slots—Their Bolts, Nuts, Tongues and Cutters
ANSI B5.8-1972 (R1979)	Chucks and Chuck Jaws
ANSI B5.9-1967 (R1972)	Spindle Noses for Tool Room Lathes, Engine Lathes, Turret Lathes, and Automatic Lathes
ANSI B5.10-1963 (R1972)	Machine Tapers
ANSI B5.11-1964 (R1973)	Spindle Noses and Adjustable Adapters for Multiple Head Spindle Drilling Heads
ANSI B5.16-1952 (R1979)	Accuracy of Engine and Tool Room Lathes
ANSI B5.18-1972	Spindle Noses and Tool Shanks for Milling Machines
ANSI B5.32-1977	Grinding Machines, Surface, Reciprocating Table—Horizontal Spindle
ANSI B5.32.1-1977	Grinding Machines, Surface, Reciprocating Table—Verticle Spindle
ANSI B5.33-1970	External Cylindrical Grinding Machines—Plain
ANSI B5.35-1969 (R1975)	Machine Mounting Specifications for Abrasive Discs and Plate Mounted Wheels
ANSI B5.37-1970	External Cylindrical Grinding Machines—Centerless
ANSI B5.40-1977	Spindle Noses and Tool Shanks for Horizontal Boring Machines
ANSI B5.41-1968 (R1973)	Quill Flanges and Spindle Ends for Upright and Horizontal Drill Spindles for Production Type Drilling Machines
ANSI B5.42-1970	External Cylindrical Grinding Machines—Universal
ANSI B5.43M-1979	Modular Machine Tool Standards
ANSI B5.44-1971	Rotary Table Surface Grinding Machines
ANSI B5.45-1972	Milling Machines
ANSI B5.50-1978	V Flange Tool Shanks for Machining Centers with Automatic Tool Changers
ANSI B5.51M-1979	Preferred SI Units for Machine Tools
ANSI B7.1-1978	Safety Requirements for the Use, Care, and Protection of Abrasive Wheels
ANSI B11.6-1975	Safety Requirements for the Construction and Use of Lathes
ANSI B11.8-1974	Safety Requirements for the Construction, Care and Use of Drilling, Milling and Boring Machines
ANSI B11.9-1975	Safety Requirements for the Construction, Care and Use of Grinding Machines
ANSI B11.13-1975	Safety Requirements for the Construction, Care and Use of Single and Multiple-Spindle Automatic Screw/Bar and Chucking Machines
ANSI B46.1-1978	Surface Texture, Surface Roughness, Waviness and Lay
ANSI B52.1-1962	Classification of Materials for Tools, Fixtures, and Gages
ANSI B67.1-1975	Diamond Dressing Tools
ANSI B74.1-1966	Identification Code for Diamond Wheel Shapes
ANSI B74.2-1974	Specifications for Shapes and Sizes of Grinding Wheels and Shapes, Sizes and Identification of Mounted Wheels
ANSI B74.3-1974	Specifications for Shapes and Sizes of Diamond Grinding Wheels, Hand Hones and Mounted Wheels
ANSI B74.4-1977	Test for Bulk Density of Abrasive Grains
ANSI B74.5-1964 (R1976)	Test for Capillarity of Abrasive Grains
ANSI B74.6-1964 (R1976)	Procedure for Sampling of Abrasive Grains
ANSI B74.8-1977	Ball Mill Test for Friability of Abrasive Grain
ANSI B74.9-1970 (R1976)	Specifications for Shapes, Sizes and Identification of Mounted Wheel Mandrels
ANSI B74.10-1977	Specifications for Grading of Abrasive Microgrits
ANSI B74.11-1967 (R1978)	Specifications for Tumbling Chip Abrasives
ANSI B74.12-1977	Specifications for Size of Abrasive Grain—Grinding Wheels, Polishing and General Industrial Uses
ANSI B74.13-1977	Markings for Identifying Grinding Wheels and Other Bonded Abrasives
ANSI B74.16-1971 (R1976)	Checking the Size of Diamond Abrasive Grain

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DESIGNATION	TITLE
ANSI B74.17-1973 (R1978)	Bulk Density of Diamond Abrasive Grains. Test for
ANSI B74.18-1977	Specifications for Grading of Certain Abrasive Grain on Coated Abrasive Products
ANSI B94.1-1977	Blanks and Semi-Finished Blanks for Solid Carbide Taps
ANSI B94.2-1977	Reamers
ANSI B94.3-1965 (R1972)	Straight Cut-Off Blades for Lathes and Screw Machines
ANSI B94.4-1976	Identification System for Indexable Inserts for Cutting Tools
ANSI B94.5-1974	Carbide Blanks and Single-Point Brazed Tools
ANSI B94.6-1966 (R1972)	Knurling
ANSI B94.7-1966 (R1972)	Hobs
ANSI B94.8-1967 (R1972)	Inserted Blade Milling Cutter Bodies
ANSI B94.9-1979	Taps—Cut and Ground Threads
ANSI B94.10-1967 (R1972)	High-Speed Steel and Cast Nonferrous Single-Point Tools and Tool Holders
ANSI B94.11-1967 (R1972)	Twist Drills
ANSI B94.12-1977	Carbide-Tipped Masonry Drills and Blanks for Carbide-Tipped Masonry Drills
ANSI B94.13-1976	Blanks for Carbide Burs
ANSI B94.19-1977	Milling Cutters and End Mills
ANSI B94.20-1977	Specifications for Carbide Blanks for Twist Drills. Reamers. End Mills. and Random Rod
ANSI B94.21-1968 (R1974)	Gear Shaper Cutters
ANSI B94.24-1976	Heavy Duty Carbide Inserts for Cutting Tools
ANSI B94.25-1975	Indexable Inserts for Cutting Tools
ANSI B94.26-1969	Indexable (Throw-Away) Insert Holders
ANSI B94.32-1954 (R1971)	Circular and Dove Tailed Forming Tool Blanks
ANSI B94.33-1974	Jig Bushings
ANSI B94.34-1946 (R1971)	Life Tests of Single-Point Tools Made of Materials Other Than Sintered Carbides
ANSI B94.35-1972	Drill Drivers—Split-Sleeve, Collet-Type
ANSI B94.36-1956 (R1971)	Life Tests for Single-Point Tools of Sintered Carbide
ANSI B94.37-1972	Carbide Blanks and Cutting Tools. Single-Point. Carbide-Tipped. Roller Turner Type
ANSI B94.42-1972 (R1978)	Carbide Blanks for Tipping Circular Saws
ANSI B94.45-1973	Precision Indexable Insert Holders
ANSI B94.46-1973	Carbide Seats Used with Indexable Inserts for Clamp Type Holders
ANSI B94.47-1973	Carbide Chip Breakers Used with Indexable Inserts for Clamp Type Holders
ANSI B94.48-1976	Precision Indexable Insert Cartridges
ANSI B94.49-1975	Spade Drill Blades and Spade Drill Holders
ANSI B94.50-1975	Single-Point Cutting Tools. Basic Nomenclature and Definitions for
ANSI B94.51-1976 (1977)	Specifications for Band Saw Blades (Metal Cutting)
ANSI B94.52-1977	Hack Saw Blades
ANSI B104.1-1964	Dimensions for Diamond Core Drill (DCDMA Bulletin No. 2)
ANSI B122.1-1970	Band Saw Blades
ANSI C85.1-1963	Terminology for Automatic Control (includes 1966. 1972 supplements)
ANSI H9.7-1973	Recommended Practice for Evaluating Cemented Carbides for Apparent Porosity (ASTM B276-54. reaffirmed 1972)
ANSI H9.10-1973	Method for Hardness Testing of Cemented Carbides
ANSI H9.24-1973	Test for Electrical Resistivity of Cemented Tungsten Carbides (ASTM B421-76)
ANSI H9.26-1969 (R1974)	Method for Tension Testing of Cemented Carbides (ASTM B437-67)
ANSI/SAE J1173-1977	Size Classification and Characteristics of Glass Beads for Peening
ANSI X3.37-1977	Programming Language APT
ANSI X8.1-1968	Axis and Motion Nomenclature for Numerically Controlled Machines (EIA RS-267-A)
ANSI X8.2-1968	Interchangeable Perforated Tape Vairable Block Format for Positioning, Contouring and Contouring/Positioning Numerically Controlled Machine Tools (EIA RS-274-C)
ANSI X8.3-1968	Interchangeable Perforated Tape Variable Block Format for Positioning and Straight Cut Numerically Controlled Machine Tools (EIA RS-273-A)

DESIGNATION	TITLE
ANSI Y14.5-1973	Dimensioning and Tolerancing
ANSI Y14.36-1978	Surface Texture Symbols
ANSI Z11.142-1964 (R1974)	Method of Test for Emulsion Stability of Soluble Cutting Oils (ASTM D1479-64-1968)
ANSI Z43.1-1966	Ventilation Control of Grinding, Polishing, and Buffing Operations
ANSI Z49.1-1973	Safety in Welding and Cutting
ANSI Z94.10-1972	Production Planning and Control
ANSI Z94.12-1972	Work Measurement and Methods
ASTM A 597-75	Specification for Cast Tool Steel
ASTM A 600-76	Specification for High-Speed Tool Steel
ASTM B 276-54 (1972)	Recommended Practice for Evaluating Cemented Carbides for Apparent Porosity (ANSI H9.7-1973)
ASTM B 294-76	Standard Method for Hardness Testing of Cemented Carbides (ANSI H9.10-1973)
ASTM B 311-58 (1972)	Test for Density of Cemented Carbides (Approved by ANSI)
ASTM B 390-64 (1976)	Evaluating Apparent Grain Size and Distribution of Cemented Tungsten Carbides (Approved by ANSI)
ASTM B 406-76	Test for Determination of Transverse Rupture Strength of Cemented Carbides (Approved by ANSI)
ASTM B 421-76	Test for Electrical Resistivity of Cemented Tungsten Carbides (ANSI H9.24-1973)
ASTM B 437-67 (1973)	Tension Testing of Cemented Carbides (ANSI H9.26-1969)
ASTM B 485-76	Method for Diametral Compression Testing of Cemented Carbides
ASTM B 611-76	Test for Abrasive Wear Resistance of Cemented Carbides
ASTM D 88-56 (1973)	Test for Saybolt Viscosity (Approved by ANSI)
ASTM D 92-72 (1977)	Test for Flash and Fire Points by Cleveland Open Cup (Approved by ANSI)
ASTM D 94-71 (1976)	Test for Saponification Number by Color-Indicator Tritration (Approved by ANSI)
ASTM D 129-64 (1973)	Test for Sulfur in Petroleum Products by the Bomb Method (Approved by ANSI)
ASTM D 130-75	Test for Detection of Copper Corrosion from Petroleum Products by the Copper Strip Tarnish Test (Approved by ANSI)
ASTM D 156-64 (1977)	Test for Saybolt Color of Petroleum Products, Saybolt Chromometer Method (Approved by ANSI)
ASTM D 287-67 (1977)	Test for API Gravity of Crude Petroleum and Petroleum Products, Hydrometer Method (Approved by ANSI)
ASTM D 445-74	Test for Viscosity of Transparent and Opaque Liquids, Kinematic and Dynamic Viscosities (Approved by ANSI)
ASTM D 808-63 (1976)	Test for Chlorine in New and Used Petroleum Products—Bomb Method (Approved by ANSI)
ASTM D 892-74	Test for Foaming Characteristics of Lubricating Oils (Approved by ANSI)
ASTM D 1479-64 (1973)	Test for Emulsion Stability of Soluble Cutting Oils (ANSI Z11.142-1964, reaffirmed 1972)
ASTM D 1662-69 (1974)	Test for Active Sulfur in Cutting Fluids (Approved by ANSI)
ASTM D 1666-64 (1976)	Conducting Machining Tests of Wood and Wood-Base Materials
ASTM D 2670-67 (1977)	Measuring Wear Properties of Fluid Lubricants—Falex Method (Approved by ANSI)
ASTM E 352-76a	Methods for Chemical Analysis of Tool Steel and Other Similar Medium- and High-Alloy Steels
ASTM E 618-77T	Evaluating Machining Performance Using an Automatic Screw/Bar Machine
AWS A6.3-69	Recommended Safe Practices for Plasma Arc Cutting
AWS C4.1-77	Criteria for Describing Oxygen-Cut Surfaces
AWS C5.2-73	Recommended Practices for Plasma-Arc Cutting
AWS C5.3-74	Recommended Practices for Air Carbon-Arc Gouging and Cutting
AWS F2.1-78	Recommended Safe Practices for Electron Beam Welding and Cutting
DWMI 101	Variables Affecting Diamond Wheels in Carbide Grinding
DWMI 102	Test Procedures for Grinding Carbides with Coolants
DWMI 103	Test Procedures for Dry Grinding Tungsten Carbide with Resinoid Bonded Diamond Wheels
DWMI 104	Test Procedures for Evaluating Diamond Circular Saw Blades Cutting Non-Metallic Materials

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DESIGNATION	TITLE
DWMI 105	Diamond Grinding of Carbides
DWMI 106	Techniques for Consumer Evaluation of Resinoid Grinding Wheels
EIA Automation Bulletin No. 3-C	Glossary of Terms for Numerically Controlled Machines
EIA Automation Bulletin No. 4	Recommended Interchangeable Perforated Tape Variable Block Format for Contouring and Positioning Numerically Controlled Stored Program Machines
EIA RS-227A	One Inch Perforated Tape
EIA RS-244B	Character Code for Numerical Machine Control Perforated Tape
EIA RS-267A	Axis and Motion Nomenclature for Numerically Controlled Machines (ANSI X8.1-1968)
EIA RS-274C	Interchangeable Perforated Tape Variable Block Format for Positioning, Contouring and Contouring/Positioning Numerically Controlled Machines (ANSI X8.2-1968)
EIA RS-281A	Electrical and Construction Standards for Numerical Machine Control
EIA RS-358A	Subset of American National Standard Code for Information Interchange (ASCII) for Numerical Machine Control Perforated Tape
EIA RS-408	Interface between Numerical Control Equipment and Data Terminal Equipment Employing Parallel Binary Data Interchange
EIA RS-431	Electrical Interface between Numerical Control and Machine Tools
FIA RS-447	Operational Command and Data Format for Numerically Controlled Machines
GGG-B-421C	Blades, Band-Saw Wood Cutting, Metal Cutting, and Meat Cutting
GGG-B-431A(1)	Blades, Saw, Round (Machine and Hand)
GGG-B-461A	Blocks, Step, Machinists'
GGG-C-350B	Chucks, Drills; Adapters, Arbors, and Keys, Drill Chuck
GGG-C-755E	Cutters, Milling
GGG-D-751C(2)	Drills, Twist (Taper-Square, Straight, and Taper-Round Shanks)
GGG-F-00340(2)	Files, Rotary
GGG-P-446A	Plate, Lapping
GGG-S-66B (SH)	Saws, Hole: Blades, Hole Saw and Arbors, Hole Saw
GGG-V-191D	V-Block and Clamp
GGG-V-443A	Vises, Machine Table: Bench and Machine Table: Contour Gripping
GGG-W-220B(1)	Wedges, Steel
GGG-W-290B	Wheels, Abrasive, Snagging
GGG-W-301B	Wheel, Buffing and Polishing
ISO 229-1973	Machine Tools—Speeds and Feeds
ISO/R 230-1961	Machine Tool Test Code
ISO 235/1-1975	Parallel Shank Twist Drills, Jobber and Stub Series, Morse Taper Shank Twist Drills and Core Drills
ISO 235/2-1972	Core Drills with Parallel Shanks and Morse Taper Shanks—Recommended Stocked Sizes
ISO 236/1-1976	Hand Reamers
ISO 236/2-1976	Long Fluted Machine Reamers, Morse Taper Shanks
ISO 240-1975	Milling Cutters—Interchangeability Dimensions for Cutter Arbors or Cutter Mandrels—Metric Series and Inch Series
ISO 242-1975	Carbide Tips for Brazing on Turning Tools
ISO 243-1975	Turning Tools with Carbide Tips—External Tools
ISO/R 468-1966	Surface Roughness
ISO 494-1975	Parallel Shank Twist Drills—Long Series
ISO 504-1975	Turning Tools with Carbide Tips—Designation and Marking
ISO 513-1975	Application of Carbides for Machining by Chip Removal—Designation of the Main Groups of Chip Removal and Groups of Application
ISO 514-1975	Turning Tools with Carbide Tips—Internal Tools
ISO 521-1975	Machine Chucking Reamers with Parallel Shanks or Morse Taper Shanks
ISO 522-1975	Special Tolerances for Reamers
ISO 523-1974	Milling Cutters—Recommended Range of Outside Diameters
ISO 525-1975	Bonded Abrasive Products—General Features—Designation, Ranges of Dimensions, and Profiles

DESIGNATION	TITLE
ISO 529-1975	Short Machine Taps and Hand Taps
ISO/R 603-1967	Bonded Abrasive Products–Grinding-Wheel Dimensions (Part I)
ISO 883-1976	Indexable (Throwaway) Carbide Inserts without Fixation Hole–Dimensions
ISO 1117-1975	Bonded Abrasive Products–Grinding-Wheel Dimensions (Part II)
ISO 1302-1974	Method of Indicating Surface Texture on Drawings
ISO 1641/1-1978	End Mills and Slot Drills–Part I: Milling Cutters with Parallel Shanks
ISO 1641/2-1978	End Mills and Slot Drills–Part II: Milling Cutters with Morse Taper Shanks
ISO 1641/3-1978	End Mills and Slot Drills–Part III: Milling Cutters with 7/24 Taper Shanks
ISO 1701-1974	Test Conditions for Milling Machines with Table of Variable Height, with Horizontal or Vertical Spindle–Testing of the Accuracy
ISO 1708-1975	Test Conditions for General Purpose Parallel Lathes–Testing of the Accuracy
ISO 1832-1977	Indexable (Throwaway) Inserts for Cutting Tools–Designation–Code of Symbolization
ISO 1878-1974	Classification of Instruments and Devices for Measurement and Evaluation of the Geometrical Parameters of Surface Finish
ISO 1879-1974	Instruments for the Measurement of Surface Roughness by the Profile Method–Vocabulary
ISO 1880-1979	Instruments for the Measurement of Surface Roughness by the Profile Method–Contact (Stylus) Instruments of Progressive Profile Transformation–Profile Recording Instruments
ISO 1929-1974	Abrasive Belts–Designation, Dimensions and Tolerances
ISO 1984-1974	Test Conditions for Milling Machines with Table of Fixed Height with Horizontal or Verticle Spindle–Testing of Accuracy
ISO 1985-1974	Test Conditions for Surface Grinding Machines with Vertical Grinding Wheel Spindle and Reciprocating Table–Testing of Accuracy
ISO 1986-1974	Test Conditions for Surface Grinding Machines with Horizontal Grinding Wheel Spindle and Reciprocating Table–Testing of Accuracy
ISO 2250-1972	Finishing Reamers for Morse and Metric Tapers, with Parallel Shanks and Morse Taper Shanks
ISO 2283-1972	Long Shank Machine Taps with Nominal Diameters from 3 to 24 mm and 1/8 to 1 inch, with Amendment 1-1977
ISO 2296-1972	Metal Slitting Saws with Fine and Coarse Teeth–Metric Series
ISO 2306-1972	Drills for Use Prior to Tapping Screw Threads
ISO 2324-1972	End Mills with 7/24 Taper Shanks–Standard Series and Long Series
ISO 2336-1972	Hand and Machine Hacksaw Blades–Dimensions for Lengths up to 450 mm and Pitches up to 6.3 mm
ISO 2407-1973	Test Conditions for Internal Cylindrical Grinding Machines with Horizontal Spindle–Testing of Accuracy
ISO 2423-1974	Test Conditions for Radial Drilling Machines with the Arm Adjustable in Height–Testing of the Accuracy
ISO 2433-1973	Test Conditions for External Cylindrical Grinding Machines with a Movable Table–Testing of Accuracy
ISO 2584-1972	Cylindrical Cutters with Plain Bore and Key Drive–Metric Series
ISO 2585-1972	Slotting Cutters with Plain Bore and Key Drive–Metric Series
ISO 2587-1972	Side and Face Milling Cutters with Plain Bore and Key Drive–Metric Series
ISO 2632/1-1975	Roughness Comparison Specimens–Part I: Turned, Ground, Bored, Milled, Shaped and Planed
ISO 2632/2-1977	Roughness Comparison Specimens–Part II: Spark-Eroded, Shot Blasted and Grit Blasted, and Polished
ISO 2772/1-1973	Test Conditions for Box Type Vertical Drilling Machines–Testing of the Accuracy–Part I: Geometrical Tests
ISO 2772/2-1974	Test Conditions for Box Type Vertical Drilling Machines–Testing of the Accuracy–Part II: Practical Test
ISO 2773/1-1973	Test Conditions for Pillar Type Vertical Drilling Machines–Testing of the Accuracy–Part I: Geometrical Tests
ISO 2773/2-1973	Test Conditions for Pillar Type Vertical Drilling Machines–Testing of the Accuracy–Part II: Practical Test

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DESIGNATION	TITLE
ISO 2780-1973	Milling Cutters with Tenon Drive–Interchangeability Dimensions with Cutter Arbors–Metric Series
ISO 2857-1973	Ground Thread Taps for ISO Metric Threads of Tolerances 4H to 8H and 4G to 6G Coarse and Fine Pitches–Manufacturing Tolerances on the Threaded Portion
ISO 2924-1973	Solid and Segmental Circular Saws for Cold Cutting of Metals–Interchangeability Dimensions of the Drive–Saw Diameter Range 224 to 2240 mm
ISO 2933-1974	Bonded Abrasive Products–Grinding Wheel Dimensions (Part III)
ISO 2940/1-1974	Milling Cutters Mounted on Centring Arbors having a 7/24 Taper–Part I: Fitting Dimensions–Centring Arbors
ISO 2940/2-1974	Milling Cutters Mounted on Centring Arbors having a 7/24 Taper–Part II: Inserted Tooth Cutters
ISO 2976-1973	Abrasive Belts–Selection of Width/Length Combinations
ISO 3002/1-1977	Geometry of the Active Part of Cutting Tools–Part I. General Terms, Reference Systems, Tool and Working Angles
ISO 3070/0-1975	Test Conditions for Boring and Milling Machines with Horizontal Spindle–Testing of the Accuracy–Part 0: General Introduction
ISO 3070/1-1975	Test Conditions for Boring and Milling Machines with Horizontal Spindle–Testing of the Accuracy–Part 1: Table Type Machines
ISO 3274-1975	Instruments for the Measurement of Surface Roughness by the Profile Method–Contact (Stylus) Instruments of Consecutive Profile Transformation–Contact Profile Meters, System M
ISO 3293-1975	Morse Taper Shank Countersinks for Angles 60 degrees, 90 degrees and 120 degrees inclusive
ISO 3294-1975	Parallel Shank Countersinks for Angles 60, 90 and 120 degrees inclusive
ISO 3314-1975	Shell Drills with Taper Bore (Taper Bore 1:30 (included)) with Slot Drive
ISO 3337 1975	T-Slot Cutters with Plain or Flatted Parallel Shanks and with Morse Taper Shanks having Tapped Hole–Metric Series
ISO 3364-1977	Indexable (Throwaway) Carbide Inserts with Cylindrical Fixation Hole–Dimensions
ISO 3365/1-1977	Indexable (Throwaway) Carbide Inserts for Milling Cutters–Dimensions–Part I–Square Inserts
ISO 3438-1975	Subland Twist Drills with Morse Taper Shanks for Holes Prior to Tapping Screw Threads
ISO 3439-1975	Subland Twist Drills with Parallel Shanks for Holes Prior to Tapping Screw Threads
ISO 3442-1975	Self-Centring Chucks for Machine Tools with Two-Piece Jaws (Tongue and Groove Type)–Sizes for Interchangeability and Acceptance Test Specifications
ISO 3465-1975	Hand Taper Pin Reamers
ISO 3466-1975	Machine Taper Pin Reamers with Parallel Shanks
ISO 3467-1975	Machine Taper Pin Reamers with Morse Taper Shanks
ISO/TR 3498-1974	Lubricants for Machine Tools
ISO 3655/0-1976	Test Conditions for Vertical Turning and Boring Lathes with One or Two Columns–Testing of the Accuracy - Part 0: General Introduction
ISO 3655/1-1976	Test Conditions for Vertical Turning and Boring Lathes with One or Two Columns–Testing of the Accuracy–Part 1: Lathes with a Single Fixed or Movable Table
ISO 3685-1977	Tool-Life Testing with Single-Point Turning Tools
ISO 3686-1976	Test Conditions for Turret and Single Spindle Co-ordinate Drilling and Boring Machines with Table of Fixed Height with Vertical Spindle–High Accuracy Machines–Testing of the Accuracy
ISO 3855-1977	Milling Cutters–Nomenclature Bilingual Edition
ISO 3859-1977	Inverse Dovetail Cutters and Dovetail Cutters with Parallel Shanks
ISO 3860-1976	Bore Cutters with Key Drive–Form Milling Cutters with Constant Profile
ISO 3919-1977	Coated Abrasives–Flap Wheels with Shafts–Designation and Dimensions
ISO 3920-1976	Honing Stones of Square Section–Designation and Dimensions
ISO 3921-1976	Honing Stones of Rectangular Section–Designation and Dimensions
ISO 3940-1977	Tapered Die-Sinking Cutters with Parallel Shanks
ISO 4204-1977	Countersinks, 90 degrees, with Morse Taper Shanks and Detachable Pilots
ISO 4205-1977	Countersinks, 90 degrees, with Parallel Shanks and Solid Pilot
ISO 4206-1977	Counterbores with Parallel Shanks and Solid Pilots

DESIGNATION	TITLE
ISO 4207-1977	Counterbores with Morse Taper Shanks and Detachable Pilots
ISO 4208-1977	Detachable Pilots for Use with Counterbores and 90 degrees Countersinks–Dimensions
ISO 4703-1977	Test Conditions for Surface Grinding Machines with Two Columns–Machines for Grinding Slideways–Testing of Accuracy
ISO 4875/1-1978	Metal Cutting Band Saw Blades–Part I: Definitions and Terminology
ISO 5169-1977	Machine Tools–Presentation of Lubrication Instructions
ISO 5170-1977	Machine Tools–Lubrication Systems
ISO 5421-1977	Ground High Speed Steel Tool Bits
ISO 5429-1977	Coated Abrasives–Flap Wheels with Incorporated Flanges or Separate Flanges–Designation and Dimensions
MIL-B-4554B	Boring, Drilling and Milling Machine, Horizontal, Table Type, Heavy Duty, 3, 4 and 5 Inch Spindle
MIL-B-9925C	Boring Machine, Jig, Vertical, Manual Control
MIL-B-80004B	Boring and Milling Machine, Precision, Horizontal Spindle, Table Type, Manually or Numerically Controlled
MIL-B-80012B	Boring and Turning Machines, Vertical, and Lathes, Vertical, Turret, Manual
MIL-B-80094B	Boring, Drilling and Milling Machines, Horizontal Spindle, Table Type, Numerically Controlled, Perforated Tape
MIL-B-80202(1)	Boring and Turning Machines, Vertical, Numerically Controlled, Perforated Tape
MIL-B-80203	Broaching Machine, Hydraulic, Horizontal, Internal, Single Ram, Manual Control
MIL-B-80210A	Boring Machine, Jig, Vertical, Numerically Controlled Perforated Tape
MIL-B-80248(1)	Boring and Turning Machines, Vertical, Numerical Control by Manual Data Input 36 Through 96 Inch Tables
MIL-C-936	Counterbore and Spot-facer, Adjustable
MIL-C-45044	Cutting-grooving-beveling Machine, Pipe, Gasoline Engine Driven, Skid Mounted, 8-Inch Capacity
MIL-C-45576	Chuck, Centering, Lathe(L)
MIL-C-45833C	Chuck, Independent Jaw (Medium Duty)
MIL-C-46113B	Cutting-fluid Concentrates, Transparent
MIL-C-46149	Cutting Fluid, Sulfur and Chlorine Additive
MIL-C-80021A(1)	Cut-off Machine, Abrasive Disk or Circular Saw Blade, Metalcutting, Chop Stroke, Dry Cut, Floor Mounted
MIL-C-80036B	Cutting Machine, Oxygen Flame and Plasma Arc, Automatic, Stationary
MIL-C-80071A	Cutoff Machine, Abrasive Disk, Metal-Cutting, Wet Cut
MIL-C-80090B	Cutting System, Metal, Plasma Arc
MIL-D-3141B	Drilling Machine, Upright, Round Column, Floor Type, 21 Inch Swing,(L) Superseded by MIL-D-80002
MIL-D-17674D	Drilling Machine, Upright, Back-geared, Fixed Head, 21-Inch Swing, 1-1/2 Inch Drill(L)
MIL-D-18072C	Drilling Machine, Upright, Sensitive, Bench Type, Single Spindle, 5/16 Inch and Under, Hand Feed
MIL-D-45815C	Drilling Machine, Radial, Bench Type, Sliding Arm, Swivel Head, Hand Feed
MIL-D-80000C	Drilling Machine, Upright, Round Column, Floor and Pedestal, Hand Feed
MIL-D-80002C	Drilling Machine, Upright, Round and Box Column, Sliding Head, Plain Table, Power Feed
MIL-D-80010C(1)	Drilling Machine, Upright, Turret Head, Automatic, 3/4 to 1-1/2 Inch Drill Capacity
MIL-D-80017B	Drilling Machine, Upright, Round and Box Column Sliding Head, Floor Mounted, Geared Drive, Power Feed
MIL-D-80038B(1)	Drilling Machine, Upright, Bench Type, Round Column, Electric Motor Driven, Hand Feed
MIL-D-80039A(1)	Drilling Machine, Upright, Bench Type, Box Column, Sliding Head, Electric Motor Driven, Hand Feed
MIL-D-80076B	Drilling Machine, Upright, Box Column, Floor, Plain Table, Hand Feed

L = Limited coordination document

25.2 Alphabetical List of Machining Standards

DESIGNATION	TITLE
MIL-D-80077B	Drilling Machine, Upright, Turret Type, Sliding Head, Bed Type, Numerically Controlled
MIL-D-80078B	Drilling Machine, Upright, Turret Head, Traveling Column, Numerically Controlled, Perforated Tape
MIL-D-80084A	Drilling Machine, Upright, Turret Type, Fixed Clearance, Sliding Turret Carrier, Numerically Controlled
MIL-D-80150A	lling Machine, Upright, Turret Head, Sliding Carrier, Six Spindles, Bench Mounted
MIL-D-80193A	Drilling Machine, Vertical, Multi-Spindle, Adjustable Joint, Standard
MIL-D-80225	Drilling Machine, Deep Hole, Horizontal Spindle, Floor Mounted, Gun Type
MIL-E-80022A	Electro Erosion Machine, Electrolytic, Carbide Tool Bit and Chip Breaker Grinder
MIL-E-80023B	Electrical Discharge Machine, Vertical, Electro-Erosion Machine, Electrical Discharge, Vertical, Ram and Quill Type (Non-rotating, Non-tilting Head)
MIL-E-80100A	Electro-erosion Machine, Metal, Electro-chemical, Vertical Ram Type, Cavity Sinking
MIL-E-80130A	Electro-erosion Machine, Metal Disintegrating, Electric Arc, Vibrating Head, Drill Type
MIL-E-80140B	Electro-erosion Machine, Electrical Discharge, Horizontally Moving Head, Bridge Type
MIL-E-80157A	Electro-erosion Machine, Electrical Discharge, Angular Tilting Quill Head, Rotating Ram, Knee Type Bed
MIL-E-80158A	Electro-erosion Machine, Electrical Discharge, (C) Frame, Angular Tilting Head, Quill Type, Rotating Spindle
MIL-E-80222	End Finishing Machine, Tube and Rod, Deburring, Chamfering, and Facing, Bench and Floor Mounted, 2, 3 and 5 Inch Diameter Workpiece Capacity
MIL-E-80238	Electro-erosion Machine, Electro-chemical, Horizontal Ram Type, Cavity Sinking
MIL-F-12490B	Filing Machine, Saw Blade(L)
MIL-F-23808	Filing Machine, Saw Blade, Band and Circular, Automatic(L)
MIL-G-4515B	Grinding Machine, Knife, Horizontal Spindle, Electric Motor Driven
MIL-G-19120B	Grinding Machines, Saw Tooth, Hand Operated, Electric Motor Driven(L)
MIL-G-23368B(1)	Grinding Machine, Cylindrical, External, Plain, ower
MIL-G-23681B	Grinding Machine, Jig, Vertical
MIL-G-23823C	Grinding Machine, Cylindrical, External, Center Type, Universal, Traveling Table
MIL-G-23900C	Grinding Machine, Universal and Tool
MIL-G-45072E	Grinding Machine, Drill, Manual Operation
MIL-G-80025A	Grinding Machine, Carbide Tool Bit, Floor Type, Electric Motor Driven
MIL-G-80048B(1)	Grinding Machine, Centerless, External, Cylindrical
MIL-G-80065B	Grinding Machine, Drill Point, Floor Mounted, Vertical Spindle, Automatic Cycle
MIL-G-80066B	Grinding Machine, Internal Chucking, Plain, Horizontal, Electric Motor Driven
MIL-G-80073B	Grinding Machine, Internal, Chucking, Universal
MIL-G-80088B	Grinding Machine, Surface, Refiprocating Table, Horizontal Spindle, Power Feed
MIL-G-80125A	Grinding Machine, Surface, Rotary, Vertical Spindle, Single Table
MIL-G-80126A	Grinding Machine, Disc, Horizontal, Double End, Single Spindle
MIL-G-80143A	Grinding Machine, Plunge, External, Multi-Form
MIL-G-80145A	Grinding Machine, Surface, Reciprocating Table, Horizontal Spindle, Hand Feed
MIL-G-80162A	Grinding Machine, Thread, External, Automatic
MIL-G-80163A	Grinding Machine, Surface, Rotary Table, Horizontal Spindle
MIL-G-80176A	Grinding Machine, Abrasive Belt, Platen Type, Light, Medium and Heavy Duty, 4, 6, 8, and 10 Inch Belt Widths
MIL-G-80179	Grinding Machine, Center Hole, Vertical, Floor Mounted, Electric Motor Driven
MIL-G-80180A	Grinding Machine, Internal, Chucking, Horizontal, Electric Motor Driven
MIL-G-80189	Grinding Machine, Circular Saw Blade, Automatic
MIL-G-80194	Gear Hobbing Machines, Vertical
MIL-G-80195	Gear Hobbing Machines, Horizontal, Mechanical

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DESIGNATION	TITLE
MIL-G-80196	Gear Hobbing Machines, Horizontal, Hydraulic
MIL-G-80228	Grinding Machine, Internal, Planetary Head, Horizontal Spindle, Electric Motor Driven
MIL-G-80239	Grinding Machine Inside/Outside, Surface, Rotary Table Vertical Spindle, Universal
MIL-H-938	Hole-cutters and Hole-saws
MIL-H-4081B(2)	Holder, Countersink, Adjustable Micrometer Stop and Cutters, Countersink
MIL-H-80003B	Honing Machine, Vertical, Single Spindle, 1-1/2 to 12 Inch Bore, 12 to 80 Inch Stroke
MIL-H-80009B	Honing Machines, Horizontal, Single Spindle, Mandrel Type, Wet Application
MIL-H-80216	Honing Machine, Horizontal, Internal, Single Spindle, Long Stroke (8 Feet to 25 Feet)
MIL-K-80221	Keyseating Machine, Mechanical and Hydraulic, Reciprocating Cutter Type
MIL-L-4370B	Lathe, Engine, Heavy Duty, 4025, and 40-Inch Swing, Raised and Hollow Spindle
MIL-L-4533D	Lathe, Turret, Horizontal, Universal, Ram Type
MIL-L-11285B	Lathe, Engine, 9 by 22 Inch Capacity, Bench Type(L)
MIL-L-13896D(2)	Lathe, Engine, Gap, Sliding Bed
MIL-L-17966D	Lathe, Engine, Geared Head, 21 and 26 Inch
MIL-L-19368B	Lathe, Engine, Motor Driven, Bench, 16 Inch Swing, Nodular Iron Construction, Submarine Use(L)
MIL-L-23225B	Lathe, Precision, Jewelers and Instrument
MIL-L-23249C(1)	Lathe, Engine and Toolroom, Light Duty, 13 and 15 Inch
MIL-L-23250B	Lathe, Engine or Toolroom, Back Gear Belt Drive, 12 Inch Through 17 Inch
MIL-L-23251B(2)	Lathe, Engine and Tool Room 2516 and 3220
MIL-L-23257B(1)	Lathe, Engine and Tool Room, Heavy Duty 1610 and 2013
MIL-L-23400B(1)	Lathe, Engine and Tool Room, 14, 16 and 20 Inch
MIL-L-45100B(1) (WC)	Lathe, Turret, Horizontal(L)
MIL-L-45943 (WC)	Lathe, Engine, Floor Mounted, 18 Inch Swing(L)
MIL-L-45958	Lathe, Engine, Floor Mounted, 25 Inch Swing(L)
MIL-L-80005A	Lapping Machine, Metalworking, High Precision, Flat Surfaces, Single Face, Free Abrasive Type
MIL-L-80006B	Lathe, Turret, Horizontal, Universal, Saddle Type
MIL-L-80007B	Lathe, Toolroom, Variable Speed, 10 Inch
MIL-L-80018A	Lathes, Turret, Horizontal, Chucking, and Bar and Chucking, Automatic, Saddle Type
MIL-L-80032B	Lathe, Chucking and Lathe, Bar, Single Spindle, Horizontal, Automatic, Turret-in-column Type
MIL-L-80053B	Lathe, Engine, Heavy Duty, Numerically Controlled, Perforated Tape
MIL-L-80061A	Lathe, Bench, Variable Speed, Plain and Turret, 9 Inch
MIL-L-80123A	Lathe, Chucking, and Lathes, Bar, Single Spindle, Horizontal, Turret-in-column Type, Automatic and Numerically Controlled by Perforated Tape
MIL-L-80175A	Lathe, Speed, Horizontal Spindle, Single End, Bench and Floor Mounted
MIL-L-80199	Lapping Machine, Flat Surfaces, Gauge Lapping Type, 7 Inch Wheel
MIL-L-80219A	Lathe, Turret, Horizontal, Vertical Bed and Slant Bed, Numerically Controlled, Perforated Tape
MIL-L-80245(1)	Lathe, Multiple Purpose, Chucking, Horizontal Spindle, Numerically Controlled, Perforated Tape
MIL-M-13934D	Milling Machine, Horizontal, Universal(L)
MIL-M-23589B	Milling Machine, Vertical, Rotary
MIL-M-23855B	Milling Machine, Vertical, Knee Type, Hydraulic, Three Dimensional, Duplicating, Profiling and Duplicating
MIL-M-45577A	Milling Machine, Swivel Head, Ram Type, Universal(L)
MIL-M-80016B	Milling Machine, Vertical, Swivel Head, Knee and Column, Ram and Turret Type
MIL-M-80033B	Milling Machine, Combination Horizontal and Vertical, Knee Type
MIL-M-80044A	Milling Machine, Horizontal, Knee Type, Number 2

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25.2 Alphabetical List of Machining Standards

DESIGNATION	TITLE
MIL-M-80051A(2)	Milling Machine, Vertical, Knee Type, Size Number 2, 28 Inches Mininum Longitudinal Travel
MIL-M-80058A(1)	Milling Machine, Vertical, Knee Type, Size No. 3 and 4, 34 and 43 Inches Minimum Longitudinal Table Travel
MIL-M-80059A(1)	Milling Machine, Vertical, Knee Type, Size No. 5 and 6, 50 and 60 Inches Minimum Longitudinal Table Travel
MIL-M-80063A(1)	Milling Machine, Horizontal, Knee Type, Size Numbers 3 and 4
MIL-M-80064A	Milling Machine, Horizontal, Knee Type, Size Numbers 5 and 6
MIL-M-80096B	Multi-Purpose Machine, Drilling, Boring, Milling and Tapping, Vertical, Single Spindle, Fixed Height Compound Table, Numerically Controlled, Perforated Tape, Manual Tool Change
MIL-M-80097A	Milling Machine, Bed Type, Vertical, 3-Dimensional Power Feed
MIL-M-80099A	Milling Machine, Bed Type, Horizontal, 3-Axis Power Feed
MIL-M-80127A	Milling Machine, Bed Type, Ram Mounted Vertical Spindle, Manual and Hydraulic Tracer Controlled Profiling and Duplicating
MIL-M-80129A	Milling Machine, Portable, Ram and Columnar Types
MIL-M-80139A	Multi-Purpose Machines, Drilling, Boring, Milling and Tapping, Vertical, Single Spindle, Compound Worktable, Numerically Controlled, Perforated Tape, Automatic Tool Changer. Superseded by MIL-M-80255.
MIL-M-80142A	Multi-Purpose Machine, Drilling, Boring, Milling and Tapping, Horizontal, Single Spindle, Fixed Height Compound Table, Numerically Controlled, Perforated Tape, Manual Tool Change
MIL-M-80155A	Milling Machines, Bed Type, Vertical Spindle, Manual and Hydraulic or Electronic Tracer Controlled
MIL-M-80168A	Milling Machine Bed Type, Vertical, Double Housing, Numerically Controlled, Profiling, 30 to 40 Horsepower Per Spindle, Single and Multi-Spindle Machines
MIL-M-80169A	Machining Center, Horizontal, Single Spindle, Integral Rotary Indexing Type Worktable, Numerically Controlled, Perforated Tape, Automatic Tool Change
MIL-M-80177A	Milling Machine, Planer Type, Double Housing
MIL-M-80182(1)	Machining Centers, Horizontal Spindle, Automatic Tool Changer, 3 Linear Axes, Rotary Machine Table, 3 and 4 Axis Numerical Controls
MIL-M-80184A	Milling Machine, Bed Type, Vertical, Double Housing, Numerically Controlled Profiling, 5 to 25 Horsepower per Spindle, Single and Multi-Spindle Machines
MIL-M-80204A	Milling Machine, Horizontal Profilers, Traveling Table Type, Three Axes, Numerically Controlled, Single and Multi-Spindle Machine
MIL-M-80206A	Milling Machine, Bed Type, Horizontal Spindle, Automatic Cycle, 14 Inch Minimum Table Width, Plain and Duplex Machines
MIL-M-80208A	Milling Machine, Horizontal Profiler, Traveling Column Type, 3 Axis, Numerically Controlled, Single and Multi-Spindle Machines
MIL-M-80209A	Milling Machines, Knee Type, Numerically Controlled, Positioning or Contouring, 1 to 4 Horsepower Spindle Drive
MIL-M-80212(1)	Milling Machine, Bed Type, Ram Mounted Vertical Spindle, Numerically Controlled Profiler
MIL-M-80213A	Milling Machine, Bed Type, Horizontal Spindle, Automatic Cycle, 18 and 20 Inch Minimum Table Width, Plain and Duplex Machines
MIL-M-80215	Milling Machine, Bed Type, Horizontal Spindle, Automatic Cycle, 24, 26 and 30 Inch Minimum Table Width, Plain and Duplex Machines
MIL-M-80255	Machining Centers, Vertical, Single Spindle, Computer Numerical Control (CNC)
MIL-P-80136A	Planers, Metal Cutting, Openside, Hydraulic, Shaper Planer Type
MIL-R-19169B	Retoothing Machine, Handsaw
MIL-S-13165B(1)	Shot Peening of Metal Parts
MIL-S-13875E	Saw, Band, Metal Cutting, 14 Inch
MIL-S-19240A(1)	Shaper, Metal-cutting Horizontal, Bench, Mechanical, 7-Inch Stroke
MIL-S-23375B	Shaper, Metal Cutting, Horizontal Ram, Hydraulic, Plain and Universal Table, Sizes 24 and 28
MIL-S-23378B	Screw Machine, Automatic, Single Spindle
MIL-S-23800A(1)	Shaper, Metal Cutting, Horizontal, Plain and Universal, Mechanical, Medium Duty 14, 16, 20 and 24 Inch Stroke

DESIGNATION	TITLE
MIL-S-23807	Saw, Circular, Traverse Cut, 8 Foot Capacity[L]
MIL-S-23847B(1)	Saw, Band, Cut Off, Horizontal, Manual and Automatic
MIL-S-23910A(2)	Shaper, Metal Cutting, Horizontal, Plain and Universal, Mechanical, Heavy Duty, 16, 20, 24, 28, 32 and 36 Inch Stroke
MIL-S-24034B	Saw, Band, Metal Cutting, Contour, Power Feed Table (3 and 7-1/2 Hp), and Non-Feeding Table (2 and 3 Hp), 16, 26, 36, and 60 Inch Throat
MIL-S-24035C	Saws, Band, Cutoff, Traveling, Tilting, Vertical Column
MIL-S-24036B	Saw, Band, Cutoff, Horizontal, Heavy Duty
MIL-S-26789B(1)	Saw, Band, Vertical, Contour, Friction Sawing, 36 Inch Throat Width, 20 Inch Throat Height
MIL-S-45814C	Saw, Band, Cutoff, Horizontal, and Combination Horizontal and Vertical
MIL-S-45957	Saw, Band, Metal Cutting, Contour, 24-Inch Throat, 12-Inch Vertical Clearance[L]
MIL-S-80001A	Shapers, Metal Cutting, Vertical, Hydraulic
MIL-S-80201A(1)	Saw, Band, Metal Cutting, Vertical, Contour
MIL-STD-852	Glass Bead Peening Procedures[L]
MIL-STD-866A	Grinding of Chrome Plated Steel and Steel Parts Heat Treated to 180,000 psi or over[L]
MIL-STD-931	Attachments and Accessories for Lathes, Metal Working
MIL-STD-932	Attachments and Accessories for Drilling and Tapping Machines
MIL-STD-938A	Attachments and Accessories for Machining Centers
MIL-STD-941A	Attachments and Accessories for Sawing and Filing Machines
MIL-STD-945A	Attachment and Accessories for Broaching Machines
MIL-STD-948A	Attachment and Accessories for Grinding Machines
MIL-STD-950A	Attachments and Accessories for Boring Machines
MIL-STD-955A	Attachments and Accessories for Electrical and Ultrasonic Erosion Machines
MIL-STD-956A	Attachments and Accessories for Milling Machines
MIL-STD-957A	Attachments and Accessories for Miscellaneous Machine Tools
MIL-STD-958A	Attachments and Accessories for Gear Cutting and Finishing Machines
MIL-STD-959A	Attachments and Accessories for Planers and Shapers
MIL-STD-1242	Machining Standards for Fire Control Material[L]
MIL-STD-1567	Work Measurement[L]
MIL-STD-1571	Steel, High Strength, Grinding of[L]
MIL-T-80166(2)	Threading Machine, Single Point, Lathe Type, Semi-Automatic (4 Inch External Thread Diameter, 4 Inch Thread Length, 4 to 40 Threads per Inch)
MIL-T-80218	Table, Rotary, Horizontal, Manual and Power Feed, Primary and Auxiliary Use, Round: 24 to 72 Inch; Rectangular: 24 x 24 to 60 x 84 Inch
MIL-W-16102C(1)	Wheel, Abrasive (Cutting-off)[Q]
MIL-W-17929B(1)	Wheel, Abrasive, Precision[Q]
MS-15687C	Cutter, Milling, Plain, Light Duty
MS-15688B	Cutter, Milling, Plain, Heavy Duty
MS-15689A	Cutter, Milling, Plain, Helical
MS-15690B	Cutter, Milling, Half-Side
MS-15691A	Cutter, Milling, Side Staggered-tooth
MS-15693A	Cutter, Milling, Metal Slitting Saw, Side-Chip Clearance
MS-15694B	Cutter, Milling, Metal Slitting Saw, Side-Chip Clearance, Staggered-tooth
MS-15695B	Cutter, Milling, Angle, Single, Plain Hole
MS-15696B	Cutter, Milling, Angle, Double
MS-15698B	Cutter, Milling, Concave
MS-15699B	Cutter, Milling, Convex
MS-15700B	Cutter, Milling, Corner Rounding
MS-15701A	Cutter, Milling, Involute Gear, 14-1/2 Degree Pressure Angle
MS-15702B	Cutter, Milling, Miter and Bevel Gear, 14-1/2 Degree Pressure Angle

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Q = Qualified products list issued

25.2 Alphabetical List of Machining Standards

DESIGNATION	TITLE
MS-15704B	Cutter, Milling, End, Single-end Multiple Flute, ASA Taper Shank
MS-15705A	Cutter, Milling, Single End, Two-Flute, Brown and Sharpe Taper Shank
MS-15706A	Cutter, Milling, Single End, Multiple Flute, Brown and Sharpe Taper Shank
MS-15707B	Cutter, Milling, End, Single-end, Two Flute, Straight Shank
MS-15708B	Cutter, Milling, End, Single-end, Multiple-flute, Straight-shank
MS-15709B	Cutter, Milling, End, Single-end, Two Flute, Flatted Straight-shank
MS-15710B	Cutter, Milling, End, Single-end, Multiple-flute, Flatted Straight-shank
MS-15711B	Cutter, Milling, End, Single-end, Ball End, Two Flute, Flatted Straight-shank
MS-15713A	Cutter, Milling, End, Double-end, Multiple-Flute, Straight-shank
MS-15714A	Cutter, Milling, End, Double-end, Two Flute, Flatted Straight-shank
MS-15715A	Cutter, Milling, End, Double-end, Multiple-Flute, Flatted Straight-shank
MS-15716B	Cutter, Milling, Shell End, Removable Shank, Spiral-flute
MS-15717B	Cutter, Milling, T-slot, Staggered Tooth, Weldon Shank
MS-15718B	Cutter, Milling, Woodruff Key-seat, Straight-shank
MS-15719B	Cutter, Milling, Screw Slotting
MS-17008	Blade, Band Saw, Metal Cutting, Flexible Back, Conventional Tooth(L)
MS-17010	Blade, Band Saw, Wood Cutting, Narrow, Spring Tempered
MS-17011	Blade, Band Saw, Wood Cutting Wide, Spring Tempered
MS-17012	Blade, Band Saw, Metal Cutting, Flexible Back, Skip Tooth General Purpose
NAS 907	High Speed Steel Twist Drills 1/16 Inch thru 1/2 Inch
NAS 909	Milling Machine–General Purpose, Knee and Bed Types, Horizontal and Vertical
NAS 910	Horizontal Boring, Drilling and Milling Machine
NAS 911	Milling Machine–Numerically Controlled Skin/Profile
NAS 912	Spar Mill, Numerically Controlled
NAS 913	Milling Machine–Numerically Controlled, Profiling and Contouring
NAS 914	Milling Machine, Tracer Controlled, Profiling and Contouring–Vertical
NAS 929	Performance Requirement–Work Holder Airframe Spar Milling Machine
NAS 931	Specification for Dual Turning Machines
NAS 932	Drills–Threaded Hexagonal Shank Sizes #40 thru Letter "F"
NAS 936	Milling Machine–Precision Bed-Type, Horizontal and Vertical Spindles
NAS 937	Drills–Procurement Specification Stepped Double Margin Sizes 5/32 Inch thru 1/2 Inch
NAS 938	Machine Axis and Motion Nomenclature
NAS 943	Interchangeable Perforated Tape Standards Variable Block Format for Positioning and Straight Cut Numerically Controlled Equipment (EIA RS-273) (Inactive for design after 30 August 1974, see NAS 955)
NAS 948	Printed Circuit Board Drilling Machine–Numerically Controlled (Inactive for design after 15 September 1975)
NAS 953	Numerical Control System
NAS 954	Numerically Controlled Horizontal Boring, Drilling and Milling Machine
NAS 955	Interchangeable Perforated Tape Standards Variable Block Format for Numerically Controlled Equipment (EIA RS-274)
NAS 960	Drilling Machines–Numerically Controlled
NAS 963	Numerically Controlled Horizontal and Vertical Jig Boring Machines
NAS 965	Drills, High Speed Steel Threaded Shank 1/16 Inch thru "F"
NAS 966	Lathe, Precision–Numerically Controlled
NAS 968	Interchangeable Digital Magnetic Tape Standards, Variable Block, Word Address Format, Contouring and Contouring/Positioning Equipment (Inactive for Design after 31 October 1974)
NAS 969	Interchangeable Digital Magnetic Tape Cartridge–For Numerically Controlled Machines (Inactive for Design after 31 October 1974)
NAS 970	Tool Holders–Basic for Numerically Controlled Machine Tools

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DESIGNATION	TITLE
NAS 971	Measuring Inspection Machine–Precision–Numerically Controlled (Inactive for Design after 15 April 1978)
NAS 973	Tool and Cutter Grinding Machine
NAS 977	Milling Machine, Contour, Numerical Control, Multiaxis, Traveling Gantry/Table, Combination High and Low Speed
NAS 978	Numerically Controlled Combination Drilling, Boring, Milling and Tapping Machines (Inactive for Design after 31 October 1974)
NAS 979	Uniform Cutting Tests–NAS Series Metal Cutting Equipment Specifications
NAS 984	Numerically Controlled Milling Machines Knee and Bed Types–Horizontal and Vertical
NAS 986	End Mills, High Speed Steel .125 Inch thru 3.00 Inch Diameter
NAS 993	Direct Numerical Control System
NAS 994	Adaptive Control System for Numerically Controlled Milling Machines
NAS 995	Computerized Numerical Control (CNC) System for Numerically Controlled Machine Tools
NAS 998	Grinder–End Mill, Numerically Controlled
NMTBA(1968)	Definition and Evaluation of Accuracy and Repeatability for Numerically Controlled Machine Tools
NMTBA(1975)	Guidelines for the Measurement of Machine Tool Utilization
OO-B-791(2)	Buffing-grinding-polishing Machines (Bench and Pedestal, Electric)
OO-C-00845	Cutter Bits, Tool Holder (Carbide Tip)
OO-C-851A(1)	Cutter Bit, Tool Holder (Solid High-speed Steel)
OO-D-565A	Dogs, Lathe
OO-D-696A	Drilling Machines, Radial, Floor Mounted
OO-G-00661B(2)	Grinding Machine, Bench, Hand-Operated
OO-G-669F	Grinder, Pneumatic, Horizontal and Vertical
OO-G-673A	Grinding Machine, Machine Tool Attachment; (Precision, Tool Post, and Angle Plate)
OO-G-692C(1)	Grinding Machine, Tool and Cutter, and Grinding and Gashing Machines, Tool, Cutter, Flute and Radius
OO-H-581A	Holders, Cutting Tool; Engine Lathe, Shaper and Planer
OO-L-125C(1)	Lathe, Engine and Toolroom, 10 Inch
OO-M-59C	Machine, Milling, Bench Type, Horizontal, Vertical, General Purpose
OO-M-340B	Milling, Grinding, Drilling, Slotting Attachment
OO-S-240E	Saw, Power, Hack (6 Inch thru 24 Inch Workpiece Capacity)
OO-S-550A	Socket, Taper-Shank Tool (Machine)
OO-T-290C	Threading Machines, Pipe and Bolt, Power Driven (Bench and Floor Type)
VV-C-846A(1)	Cutting Fluids: Emulsifiable Oils
VV-C-850A(1)	Cutting Fluids: Sulfurized Fatty and Mineral Oils
W-G-656D(3)	Grinding Machine, and Grinding and Buffing Machine Utility, Bench and Pedestal, Electric

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Sources of Machining Standards 25.3

SERIES CODE	PUBLISHER
AGMA	American Gear Manufacturers Association Standards Department 1901 North Fort Myer Drive Arlington, Virginia 22209
ANSI	American National Standards Institute, Inc. 1430 Broadway New York, New York 10018 (Many of the standards listed may also be obtained at a discount to members from: The American Society of Mechanical Engineers United Engineering Center 345 E. 47th Street New York, New York 10017)
ASTM	American Society for Testing and Materials 1916 Race Street Philadelphia, Pennsylvania 19103
AWS	American Welding Society Inc. 2501 N.W. 7th Street Miami, Florida 33125
DWMI	Diamond Wheel Manufacturers' Institute 2130 Keith Building Cleveland, Ohio 44115
EIA	Electronic Industries Association Engineering Department 2001 Eye Street, N.W. Washington, DC 20006
GGG, OO, VV, W	General Services Administration Federal Supply Service Washington, DC 20406
ISO	International Organization for Standardization Case postale 56 1211 GENEVE 20 Switzerland (ISO standards may be purchased in the U.S. from the American National Standards Institute.)
MIL, MS	Commanding Officer Naval Publications and Forms Center 5801 Tabor Avenue Philadelphia, Pennsylvania 19120
NAS	National Standards Association Inc. 427 Rugby Avenue Washington, DC 20014
NMTBA	National Machine Tool Builders' Association 7901 Westpark Drive McLean, Virginia 22101

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SECTION 26

MATERIALS INDEX

26.1 Numerical List of Materials 26-3
26.2 Alphabetical List of Materials 26-17
26.3 Chemical Composition by Material Group 26-37

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Numerical List of Materials 26.1

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
1Sb		Lead Alloys, Cast—Lead Antimony Alloys
4Sb		Lead Alloys, Cast—Lead Antimony Alloys
6Sb		Lead Alloys, Cast—Lead Antimony Alloys
8Sb		Lead Alloys, Cast—Lead Antimony Alloys
9Sb		Lead Alloys, Cast—Lead Antimony Alloys
15-5 PH	S15500	Precipitation Hardening Stainless Steel, Wrought
16-6 PH		Precipitation Hardening Stainless Steel, Wrought
16-25-6		High Temperature Alloy—Iron Base, Wrought
17-4 PH	S17400	Precipitation Hardening Stainless Steel, Wrought
17-4 PH	S17400	Precipitation Hardening Stainless Steel, Cast
17-7 PH	S17700	Precipitation Hardening Stainless Steel, Wrought
17-4 Cu Mo		Precipitation Hardening Stainless Steel, Wrought
19-9 DL	K63198	High Temperature Alloy—Iron Base, Wrought
30		Structural Steel, Wrought
35		Structural Steel, Wrought
42		Structural Steel, Wrought
45		Structural Steel, Wrought
50		Structural Steel, Wrought
50Mo-50Ag		Powder Metal Alloy—Refractory Metal Base
50W + C-50Ag		Powder Metal Alloy—Refractory Metal Base
51W-49Ag		Powder Metal Alloy—Refractory Metal Base
55		Structural Steel, Wrought
55W-45Cu		Powder Metal Alloy—Refractory Metal Base
56W + C-44Cu		Powder Metal Alloy—Refractory Metal Base
60		Structural Steel, Wrought
61Mo-39Ag		Powder Metal Alloy—Refractory Metal Base
62Cu-18Ni-18Zn-2Sn		Powder Metal Alloy—Copper-Nickel Alloy
65		Structural Steel, Wrought
65W-35Ag		Powder Metal Alloy—Refractory Metal Base
67Ni-30Cu-3Fe		Powder Metal Alloy—Nickel and Nickel Alloy
68.5Cu-30Zn-1.5Pb		Powder Metal Alloy—Brass
70		Structural Steel, Wrought
70Cu-30Zn		Powder Metal Alloy—Brass
72.5W-27.5Ag		Powder Metal Alloy—Refractory Metal Base
74W-26Cu		Powder Metal Alloy—Refractory Metal Base
75		Structural Steel, Wrought
77Cu-15Pb-7Sn-1Fe-1C		Powder Metal Alloy—Bronze
80		Structural Steel, Wrought
85		Structural Steel, Wrought
85W-15Ag		Powder Metal Alloy—Refractory Metal Base
87W-13Cu		Powder Metal Alloy—Refractory Metal Base
88Al-5Sn-4Pb-3Cu		Powder Metal Alloy—Aluminum Alloy
90		Structural Steel, Wrought
90Cu-10Ni		Powder Metal Alloy—Copper-Nickel Alloy
90Cu-10Zn		Powder Metal Alloy—Brass
90Cu-10Zn-0.5Pb		Powder Metal Alloy—Brass
90.5Al-5Sn-4Cu		Powder Metal Alloy—Aluminum Alloy
95Cu-5Al		Powder Metal Alloy—Bronze
100		Structural Steel, Wrought
101	C10100	Copper Alloy, Wrought
102	C10200	Copper Alloy, Wrought (Oxygen Free)
104	C10400	Copper Alloy, Wrought

26.1 Numerical List of Materials

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
105	C10500	Copper Alloy, Wrought
107	C10700	Copper Alloy, Wrought
109	C10900	Copper Alloy, Wrought
110	C11000	Copper Alloy, Wrought (Electrolytic Tough Pitch)
110		Structural Steel, Wrought
111	C11100	Copper Alloy, Wrought
113	C11300	Copper Alloy, Wrought (Tough Pitch With Age)
114	C11400	Copper Alloy, Wrought (Tough Pitch With Age)
115	C11500	Copper Alloy, Wrought (Tough Pitch With Age)
116	C11600	Copper Alloy, Wrought (Tough Pitch With Age)
119	C11900	Copper Alloy, Wrought
120	C12000	Copper Alloy, Wrought
120 Grade		Maraging Steel, Wrought
121	C12100	Copper Alloy, Wrought
122	C12200	Copper Alloy, Wrought (Phosphorus Deoxidized)
125	C12500	Copper Alloy, Wrought
127	C12700	Copper Alloy, Wrought
128	C12800	Copper Alloy, Wrought
129	C12900	Copper Alloy, Wrought
130	C13000	Copper Alloy, Wrought
135		Structural Steel, Wrought
140		Structural Steel, Wrought
142	C14200	Copper Alloy, Wrought
143	C14300	Copper Alloy, Wrought
145		Structural Steel, Wrought
145	C14500	Copper Alloy, Wrought
147	C14700	Copper Alloy, Wrought
150	C15000	Copper Alloy, Wrought
150		Structural Steel, Wrought
155	C15500	Copper Alloy, Wrought
160		Structural Steel, Wrought
162	C16200	Copper Alloy, Wrought
165	C16500	Copper Alloy, Wrought
165		Structural Steel, Wrought
170	C17000	Copper Alloy, Wrought (Beryllium Copper)
172	C17200	Copper Alloy, Wrought (Beryllium Copper)
173	C17300	Copper Alloy, Wrought
175	C17500	Copper Alloy, Wrought (Beryllium Copper)
180 Grade	K91940	Maraging Steel, Wrought
182	C18200	Copper Alloy, Wrought
184	C18400	Copper Alloy, Wrought
185	C18500	Copper Alloy, Wrought
185		Structural Steel, Wrought
187	C18700	Copper Alloy, Wrought
189	C18900	Copper Alloy, Wrought
190	C19000	Copper Alloy, Wrought
191	C19100	Copper Alloy, Wrought
192	C19200	Copper Alloy, Wrought
194	C19400	Copper Alloy, Wrought
195	C19500	Copper Alloy, Wrought
200 Grade		Maraging Steel, Wrought
201	S20100	Stainless Steel, Wrought—Austenitic

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
201.0	A02010	Aluminum Alloy, Cast–Sand and Permanent Mold Cast
202	S20200	Stainless Steel, Wrought–Austenitic
203EZ	S20300	Free Machining Stainless Steel, Wrought–Austenitic
208.0	A02080	Aluminum Alloy, Cast–Sand Cast
210	C21000	Copper Alloy, Wrought (Gilding, 95%)
210		Structural Steel, Wrought
213.0	A02130	Aluminum Alloy, Cast–Sand and Permanent Mold Cast
220	C22000	Copper Alloy, Wrought (Commercial Bronze 90%)
222.0	A02220	Aluminum Alloy, Cast–Sand and Permanent Mold Cast
224.0	A02240	Aluminum Alloy, Cast–Sand Cast
226	C22600	Copper Alloy, Wrought (Jewelry Bronze 87.5%)
230	C23000	Copper Alloy, Wrought (Red Brass, 85%)
240	C24000	Copper Alloy, Wrought (Low Brass, 80%)
242.0	A02420	Aluminum Alloy, Cast–Sand and Permanent Mold Cast
250 Grade	K92890	Maraging Steel, Wrought
260	C26000	Copper Alloy, Wrought (Cartridge Brass 70%)
268	C26800	Copper Alloy, Wrought (Yellow Brass)
270	C27000	Copper Alloy, Wrought (Yellow Brass)
280	C28000	Copper Alloy, Wrought (Muntz Metal)
295.0	A02950	Aluminum Alloy, Cast–Sand Cast
300 Grade	K93120	Maraging Steel, Wrought
300M	K44220	High Strength Steel, Wrought
301	S30100	Stainless Steel, Wrought–Austenitic
302	S30200	Stainless Steel, Wrought–Austenitic
302B	S30215	Stainless Steel, Wrought–Austenitic
303	S30300	Free Machining Stainless Steel, Wrought–Austenitic
303MA	S30345	Free Machining Stainless Steel, Wrought–Austenitic
303Pb	S30360	Free Machining Stainless Steel, Wrought–Austenitic
303 Plus X	S30310	Free Machining Stainless Steel, Wrought–Austenitic
303Se	S30323	Free Machining Stainless Steel, Wrought–Austenitic
304	S30400	Stainless Steel, Wrought–Austenitic
304L	S30403	Stainless Steel, Wrought–Austenitic
305	S30500	Stainless Steel, Wrought–Austenitic
308	S30800	Stainless Steel, Wrought–Austenitic
308.0	A03080	Aluminum Alloy, Cast–Sand and Permanent Mold Cast
309	S30900	Stainless Steel, Wrought–Austenitic
309S	S30908	Stainless Steel, Wrought–Austenitic
310	S31000	Stainless Steel, Wrought–Austenitic
310S	S31008	Stainless Steel, Wrought–Austenitic
314	S31008	Copper Alloy, Wrought (Leaded Commercial Bronze)
314	S31400	Stainless Steel, Wrought–Austenitic
316	S31600	Stainless Steel, Wrought–Austenitic
316	C31600	Copper Alloy, Wrought
316L	S31603	Stainless Steel, Wrought–Austenitic
317	S31700	Stainless Steel, Wrought–Austenitic
319.0	A03190	Aluminum Alloy, Cast–Sand and Permanent Mold Cast
321	S32100	Stainless Steel, Wrought–Austenitic
328.0	A03280	Aluminum Alloy, Cast–Sand Cast
330	C33000	Copper Alloy, Wrought (Low Leaded Brass)
330	N08330	Stainless Steel, Wrought–Austenitic
332	C33200	Copper Alloy, Wrought (High Lead Brass)
333.0	A03330	Aluminum Alloy, Cast–Permanent Mold Cast

26.1 Numerical List of Materials

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
335	C33500	Copper Alloy, Wrought (Low Leaded Brass)
340	C34000	Copper Alloy, Wrought (Medium Leaded Brass)
342	C34200	Copper Alloy, Wrought (High Leaded Brass)
347	S34700	Stainless Steel, Wrought—Austenitic
348	S34800	Stainless Steel, Wrought—Austenitic
349	C34900	Copper Alloy, Wrought
350	C35000	Copper Alloy, Wrought
350 Grade		Maraging Steel, Wrought
353	C35300	Copper Alloy, Wrought (High Leaded Brass)
354.0	A03540	Aluminum Alloy, Cast—Permanent Mold Cast
355.0	A03550	Aluminum Alloy, Cast—Sand and Permanent Mold Cast
356	C35600	Copper Alloy, Wrought (Extra High Leaded Brass)
356.0	A03560	Aluminum Alloy, Cast—Sand and Permanent Mold Cast
357.0	A03570	Aluminum Alloy, Cast—Sand and Permanent Mold Cast
359.0	A03590	Aluminum Alloy, Cast—Sand and Permanent Mold Cast
360.0	A03600	Aluminum Alloy, Cast—Die Casting
360	C36000	Copper Alloy, Wrought (Free Cutting Brass)
365	C36500	Copper Alloy, Wrought (Leaded Muntz Metal)
366	C36600	Copper Alloy, Wrought (Leaded Muntz Metal + As)
367	C36700	Copper Alloy, Wrought (Leaded Muntz Metal + Sb)
368	C36800	Copper Alloy, Wrought (Leaded Muntz Metal + P)
370	C37000	Copper Alloy, Wrought (Free Cutting Muntz Metal)
377	C37700	Copper Alloy, Wrought (Forging Brass)
380.0	A03800	Aluminum Alloy, Cast—Die Casting
383.0	A03830	Aluminum Alloy, Cast—Die Casting
384	S38400	Stainless Steel, Wrought—Austenitic
385	S38500	Stainless Steel, Wrought—Austenitic
385	C38500	Copper Alloy, Wrought (Architectural Bronze)
390.0	A03900	Aluminum Alloy, Cast—Die Casting
392.0	A03920	Aluminum Alloy, Cast—Die Casting
403	S40300	Stainless Steel, Wrought—Martensitic
405	S40500	Stainless Steel, Wrought—Ferritic
409	S40900	Stainless Steel, Wrought—Ferritic
410	S41000	Stainless Steel, Wrought—Martensitic
411	C41100	Copper Alloy, Wrought
413	C41300	Copper Alloy, Wrought
413.0	A04130	Aluminum Alloy, Cast—Die Casting
414	S41400	Stainless Steel, Wrought—Martensitic
416	S41600	Free Machining Stainless Steel, Wrought—Martensitic
416Se	S41623	Free Machining Stainless Steel, Wrought—Martensitic
416 Plus X	S41610	Free Machining Stainless Steel, Wrought—Martensitic
420	S42000	Stainless Steel, Wrought—Martensitic
420F	S42020	Free Machining Stainless Steel, Wrought—Martensitic
420F Se	S42023	Free Machining Stainless Steel, Wrought—Martensitic
422	S42200	Stainless Steel, Wrought—Martensitic
425	C42500	Copper Alloy, Wrought
429	S42900	Stainless Steel, Wrought—Ferritic
430	S43000	Stainless Steel, Wrought—Ferritic
430F	S43020	Free Machining Stainless Steel, Wrought—Ferritic
430F Se	S43023	Free Machining Stainless Steel, Wrought—Ferritic
431	S43100	Stainless Steel, Wrought—Martensitic
434	S43400	Stainless Steel, Wrought—Ferritic

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
435	C43500	Copper Alloy, Wrought
436	S43600	Stainless Steel, Wrought–Ferritic
440A	S44002	Stainless Steel, Wrought–Martensitic
440B	S44003	Stainless Steel, Wrought–Martensitic
440C	S44004	Stainless Steel, Wrought–Martensitic
440F	S44020	Free Machining Stainless Steel, Wrought–Martensitic
440F Se	S44023	Free Machining Stainless Steel, Wrought–Martensitic
442	C44200	Copper Alloy, Wrought (Admiralty, Uninhibited)
442	S44200	Stainless Steel, Wrought–Ferritic
443	C44300	Copper Alloy, Wrought (Admiralty + As)
444	C44400	Copper Alloy, Wrought (Admiralty + Sb)
445	C44500	Copper Alloy, Wrought (Admiralty + P)
446	S44600	Stainless Steel, Wrought–Ferritic
464	C46400	Copper Alloy, Wrought (Naval Brass)
465	C46500	Copper Alloy, Wrought (Naval Brass + As)
466	C46600	Copper Alloy, Wrought (Naval Brass + Sb)
467	C46700	Copper Alloy, Wrought (Naval Brass + P)
482	C48200	Copper Alloy, Wrought
485	C48500	Copper Alloy, Wrought (Leaded Naval Brass)
501	S50100	Stainless Steel, Wrought–Martensitic
502	S50200	Stainless Steel, Wrought–Martensitic
505	C50500	Copper Alloy, Wrought (Phosphor Bronze)
510	C51000	Copper Alloy, Wrought (Phosphor Bronze)
511	C51100	Copper Alloy, Wrought
514.0	A05140	Aluminum Alloy, Cast–Sand Cast
518.0	A05180	Aluminum Alloy, Cast–Die Casting
520.0	A05200	Aluminum Alloy, Cast–Sand Cast
521	C52100	Copper Alloy, Wrought (Phosphor Bronze)
524	C52400	Copper Alloy, Wrought (Phosphor Bronze)
535.0	A05350	Aluminum Alloy, Cast–Sand Cast
544	C54400	Copper Alloy, Wrought (Free Cutting Phosphor Bronze)
608	C60800	Copper Alloy, Wrought
610	C61000	Copper Alloy, Wrought
613	C61300	Copper Alloy, Wrought
614	C61400	Copper Alloy, Wrought (Aluminum Bronze)
618	C61800	Copper Alloy, Wrought
619	C61900	Copper Alloy, Wrought
623	C62300	Copper Alloy, Wrought
624	C62400	Copper Alloy, Wrought
625	C62500	Copper Alloy, Wrought
630	C63000	Copper Alloy, Wrought
632	C63200	Copper Alloy, Wrought
638	C63800	Copper Alloy, Wrought
642	C64200	Copper Alloy, Wrought
651	C65100	Copper Alloy, Wrought (Low Silicon Bronze)
655	C65500	Copper Alloy, Wrought (High Silicon Bronze)
667	C66700	Copper Alloy, Wrought
674	C67400	Copper Alloy, Wrought
675	C67500	Copper Alloy, Wrought (Manganese Bronze)
687	C68700	Copper Alloy, Wrought (Aluminum Brass Arsenical)
688	C68800	Copper Alloy, Wrought
694	C69400	Copper Alloy, Wrought

26.1 Numerical List of Materials

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
705.0	A07050	Aluminum Alloy, Cast–Sand and Permanent Mold Cast
706	C70600	Copper Alloy, Wrought (Copper Nickel)
707.0	A07070	Aluminum Alloy, Cast–Sand and Permanent Mold Cast
710	C71000	Copper Alloy, Wrought
713.0	A07130	Aluminum Alloy, Cast–Sand and Permanent Mold Cast
715	C71500	Copper Alloy, Wrought (Copper Nickel, 30%)
725	C72500	Copper Alloy, Wrought
745	C74500	Copper Alloy, Wrought (Nickel Silver, 65-10)
752	C75200	Copper Alloy, Wrought (Nickel Silver, 65-18)
754	C75400	Copper Alloy, Wrought (Nickel Silver, 65-15)
757	C75700	Copper Alloy, Wrought (Nickel Silver, 65-12)
770	C77000	Copper Alloy, Wrought (Nickel Silver, 58-18)
771.0	A07710	Aluminum Alloy, Cast–Sand Cast
782	C78200	Copper Alloy, Wrought
801	C80100	Copper Alloy, Cast
803	C80300	Copper Alloy, Cast
805	C80500	Copper Alloy, Cast
807	C80700	Copper Alloy, Cast
809	C80900	Copper Alloy, Cast
811	C81100	Copper Alloy, Cast
813	C81300	Copper Alloy, Cast (High)
814	C81400	Copper Alloy, Cast (High)
815	C81500	Copper Alloy, Cast (High)
817	C81700	Copper Alloy, Cast (High)
818	C81800	Copper Alloy, Cast (High)
820	C82000	Copper Alloy, Cast (High)
821	C82100	Copper Alloy, Cast (High)
822	C82200	Copper Alloy, Cast (High)
824	C82400	Copper Alloy, Cast (High)
825	C82500	Copper Alloy, Cast (High)
826	C82600	Copper Alloy, Cast (High)
827	C82700	Copper Alloy, Cast (High)
828	C82800	Copper Alloy, Cast (High)
833	C83300	Copper Alloy, Cast (Red Brass)
834	C83400	Copper Alloy, Cast (Red Brass)
836	C83600	Copper Alloy, Cast (Red Brass)
838	C83800	Copper Alloy, Cast (Red Brass)
842	C84200	Copper Alloy, Cast (Semi-Red Brass)
844	C84400	Copper Alloy, Cast (Semi-Red Brass)
848	C84800	Copper Alloy, Cast (Semi-Red Brass)
850.0	A08500	Aluminum Alloy, Cast–Sand and Permanent Mold Cast
852	C85200	Copper Alloy, Cast (Yellow Brass)
853	C85300	Copper Alloy, Cast (Yellow Brass)
854	C85400	Copper Alloy, Cast (Yellow Brass)
855	C85500	Copper Alloy, Cast (Yellow Brass)
857	C85700	Copper Alloy, Cast (Yellow Brass)
858	C85800	Copper Alloy, Cast (Yellow Brass)
861	C86100	Copper Alloy, Cast (High Strength Yellow Brass)
862	C86200	Copper Alloy, Cast (High Strength Yellow Brass)
863	C86300	Copper Alloy, Cast (High Strength Yellow Brass)
864	C86400	Copper Alloy, Cast (High Strength Yellow Brass)
865	C86500	Copper Alloy, Cast (High Strength Yellow Brass)

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
867	C86700	Copper Alloy, Cast (High Strength Yellow Brass)
868	C86800	Copper Alloy, Cast (High Strength Yellow Brass)
872	C87200	Copper Alloy, Cast (Silicon Bronze)
874	C87400	Copper Alloy, Cast (Silicon Brass)
875	C87500	Copper Alloy, Cast (Silicon Brass)
876	C87600	Copper Alloy, Cast (Silicon Brass)
878	C87800	Copper Alloy, Cast (Silicon Brass)
879	C87900	Copper Alloy, Cast (Silicon Brass)
902	C90200	Copper Alloy, Cast (Tin Bronze)
903	C90300	Copper Alloy, Cast (Tin Bronze)
905	C90500	Copper Alloy, Cast (Tin Bronze)
907	C90700	Copper Alloy, Cast (Tin Bronze)
909	C90900	Copper Alloy, Cast (Tin Bronze)
910	C91000	Copper Alloy, Cast (Tin Bronze)
911	C91100	Copper Alloy, Cast (Tin Bronze)
913	C91300	Copper Alloy, Cast (Tin Bronze)
915	C91500	Copper Alloy, Cast (Tin Bronze)
916	C91600	Copper Alloy, Cast (Tin Bronze)
917	C91700	Copper Alloy, Cast (Tin Bronze)
922	C92200	Copper Alloy, Cast (Leaded Tin Bronze)
923	C92300	Copper Alloy, Cast (Leaded Tin Bronze)
925	C92500	Copper Alloy, Cast (Leaded Tin Bronze)
926	C92600	Copper Alloy, Cast (Leaded Tin Bronze)
927	C92700	Copper Alloy, Cast (Leaded Tin Bronze)
928	C92800	Copper Alloy, Cast (Leaded Tin Bronze)
932	C93200	Copper Alloy, Cast (High Leaded Tin Bronze)
934	C93400	Copper Alloy, Cast (High Leaded Tin Bronze)
935	C93500	Copper Alloy, Cast (High Leaded Tin Bronze)
937	C93700	Copper Alloy, Cast (High Leaded Tin Bronze)
938	C93800	Copper Alloy, Cast (High Leaded Tin Bronze)
939	C93900	Copper Alloy, Cast (High Leaded Tin Bronze)
943	C94300	Copper Alloy, Cast (High Leaded Tin Bronze)
944	C94400	Copper Alloy, Cast (High Leaded Tin Bronze)
945	C94500	Copper Alloy, Cast (High Leaded Tin Bronze)
947	C94700	Copper Alloy, Cast (Nickel Tin Bronze)
948	C94800	Copper Alloy, Cast (Nickel Tin Bronze)
952	C95200	Copper Alloy, Cast (Aluminum Bronze)
953	C95300	Copper Alloy, Cast (Aluminum Bronze)
954	C95400	Copper Alloy, Cast (Aluminum Bronze)
955	C95500	Copper Alloy, Cast (Aluminum Bronze)
956	C95600	Copper Alloy, Cast (Aluminum Bronze)
957	C95700	Copper Alloy, Cast (Aluminum Bronze)
958	C95800	Copper Alloy, Cast (Aluminum Bronze)
962	C96200	Copper Alloy, Cast (Copper Nickel)
963	C96300	Copper Alloy, Cast (Copper Nickel)
964	C96400	Copper Alloy, Cast (Copper Nickel)
966	C96600	Copper Alloy, Cast (Copper Nickel)
973	C97300	Copper Alloy, Cast (Nickel Silver)
974	C97400	Copper Alloy, Cast (Nickel Silver)
976	C97600	Copper Alloy, Cast (Nickel Silver)
978	C97800	Copper Alloy, Cast (Nickel Silver)
993	C99300	Copper Alloy, Cast

26.1 Numerical List of Materials

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
1005	G10050	Carbon Steel, Wrought–Low Carbon
1006	G10060	Carbon Steel, Wrought–Low Carbon
1008	G10080	Carbon Steel, Wrought–Low Carbon
1009	G10090	Carbon Steel, Wrought–Low Carbon
1010	G10100	Carbon Steel, Wrought–Low Carbon
1010	G10100	Carbon Steel, Cast–Low Carbon
1011	G10110	Carbon Steel, Wrought–Low Carbon
1012	G10120	Carbon Steel, Wrought–Low Carbon
1013	G10130	Carbon Steel, Wrought–Low Carbon
1015	G10150	Carbon Steel, Wrought–Low Carbon
1016	G10160	Carbon Steel, Wrought–Low Carbon
1017	G10170	Carbon Steel, Wrought–Low Carbon
1018	G10180	Carbon Steel, Wrought–Low Carbon
10L18		Free Machining Carbon Steel, Wrought–Low Carbon Leaded
1019	G10190	Carbon Steel, Wrought–Low Carbon
1020	G10200	Carbon Steel, Wrought–Low Carbon
1020	J02000	Carbon Steel, Cast–Low Carbon
1021	G10210	Carbon Steel, Wrought–Low Carbon
1022	G10220	Carbon Steel, Wrought–Low Carbon
1023	G10230	Carbon Steel, Wrought–Low Carbon
1025	G10250	Carbon Steel, Wrought–Low Carbon
1026	G10260	Carbon Steel, Wrought–Low Carbon
1029	G10290	Carbon Steel, Wrought–Low Carbon
1030	G10300	Carbon Steel, Wrought–Medium Carbon
1030	J03005	Carbon Steel, Cast–Medium Carbon
1033	C10330	Carbon Steel, Wrought–Medium Carbon
1035	G10350	Carbon Steel, Wrought–Medium Carbon
1037	G10370	Carbon Steel, Wrought–Medium Carbon
1038	G10380	Carbon Steel, Wrought–Medium Carbon
1039	G10390	Carbon Steel, Wrought–Medium Carbon
1040	G10400	Carbon Steel, Wrought–Medium Carbon
1040	J04000	Carbon Steel, Cast–Medium Carbon
1042	G10420	Carbon Steel, Wrought–Medium Carbon
1043	G10430	Carbon Steel, Wrought–Medium Carbon
1044	G10440	Carbon Steel, Wrought–Medium Carbon
1045	G10450	Carbon Steel, Wrought–Medium Carbon
10L45		Free Machining Carbon Steel, Wrought–Medium Carbon Leaded
1046	G10460	Carbon Steel, Wrought–Medium Carbon
1049	G10490	Carbon Steel, Wrought–Medium Carbon
1050	G10500	Carbon Steel, Wrought–Medium Carbon
1050	J05000	Carbon Steel, Cast–Medium Carbon
10L50		Free Machining Carbon Steel, Wrought–Medium Carbon Leaded
1053	G10530	Carbon Steel, Wrought–Medium Carbon
1055	G10550	Carbon Steel, Wrought–Medium Carbon
1060	A91060	Aluminum Alloy, Wrought
1060	G10600	Carbon Steel, Wrought–High Carbon
1064	G10640	Carbon Steel, Wrought–High Carbon
1065	G10650	Carbon Steel, Wrought–High Carbon
1069	G10690	Carbon Steel, Wrought–High Carbon
1070	G10700	Carbon Steel, Wrought–High Carbon
1074	G10740	Carbon Steel, Wrought–High Carbon
1075	G10750	Carbon Steel, Wrought–High Carbon

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
1078	G10780	Carbon Steel, Wrought—High Carbon
1080	G10800	Carbon Steel, Wrought—High Carbon
1084	G10840	Carbon Steel, Wrought—High Carbon
1085	G10850	Carbon Steel, Wrought—High Carbon
1086	G10860	Carbon Steel, Wrought—High Carbon
1090	G10900	Carbon Steel, Wrought—High Carbon
1095	G10950	Carbon Steel, Wrought—High Carbon
1100	A91100	Aluminum Alloy, Wrought
1108	G11080	Free Machining Carbon Steel, Wrought—Low Carbon Resulfurized
1109	G11090	Free Machining Carbon Steel, Wrought—Low Carbon Resulfurized
1110	G11100	Free Machining Carbon Steel, Wrought—Low Carbon Resulfurized
1115		Free Machining Carbon Steel, Wrought—Low Carbon Resulfurized
1116	G11160	Free Machining Carbon Steel, Wrought—Low Carbon Resulfurized
1117	G11170	Free Machining Carbon Steel, Wrought—Low Carbon Resulfurized
11L17		Free Machining Carbon Steel, Wrought—Low Carbon Leaded
1118	G11180	Free Machining Carbon Steel, Wrought—Low Carbon Resulfurized
1119	G11190	Free Machining Carbon Steel, Wrought—Low Carbon Resulfurized
1132	G11320	Free Machining Carbon Steel, Wrought—Medium Carbon Resulfurized
1137	G11370	Free Machining Carbon Steel, Wrought—Medium Carbon Resulfurized
11L37		Free Machining Carbon Steel, Wrought—Medium Carbon Leaded
1139	G11390	Free Machining Carbon Steel, Wrought—Medium Carbon Resulfurized
1140	G11400	Free Machining Carbon Steel, Wrought—Medium Carbon Resulfurized
1141	G11410	Free Machining Carbon Steel, Wrought—Medium Carbon Resulfurized
11L41		Free Machining Carbon Steel, Wrought—Medium Carbon Leaded
1144	G11440	Free Machining Carbon Steel, Wrought—Medium Carbon Resulfurized
11L44		Free Machining Carbon Steel, Wrought—Medium Carbon Leaded
1145	A91145	Aluminum Alloy, Wrought
1145	G11450	Free Machining Carbon Steel, Wrought—Medium Carbon Resulfurized
1146	G11460	Free Machining Carbon Steel, Wrought—Medium Carbon Resulfurized
1151	G11510	Free Machining Carbon Steel, Wrought—Medium Carbon Resulfurized
1175	A91175	Aluminum Alloy, Wrought
1211	G12110	Free Machining Carbon Steel, Wrought—Low Carbon Resulfurized
1212	G12120	Free Machining Carbon Steel, Wrought—Low Carbon Resulfurized
1213	G12130	Free Machining Carbon Steel, Wrought—Low Carbon Resulfurized
12L13	G12134	Free Machining Carbon Steel, Wrought—Low Carbon Leaded
12L14	G12144	Free Machining Carbon Steel, Wrought—Low Carbon Leaded
1215	G12150	Free Machining Carbon Steel, Wrought—Low Carbon Resulfurized
12L15		Free Machining Carbon Steel, Wrought—Low Carbon Leaded
1235	A91235	Aluminum Alloy, Wrought
1320	A91235	Alloy Steel, Cast—Low Carbon
1330	G13300	Alloy Steel, Wrought—Medium Carbon
1330		Alloy Steel, Cast—Medium Carbon
1335	G13350	Alloy Steel, Wrought—Medium Carbon
1340	G13400	Alloy Steel, Wrought—Medium Carbon
1340		Alloy Steel, Cast—Medium Carbon
1345	G13450	Alloy Steel, Wrought—Medium Carbon
1513	G15130	Carbon Steel, Wrought—Low Carbon
1518	G15180	Carbon Steel, Wrought—Low Carbon
1522	G15220	Carbon Steel, Wrought—Low Carbon
1524	G15240	Carbon Steel, Wrought—Medium Carbon
1525	G15250	Carbon Steel, Wrought—Medium Carbon
1526	G15260	Carbon Steel, Wrought—Medium Carbon

26.1 Numerical List of Materials

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
1527	G15270	Carbon Steel, Wrought–Medium Carbon
1536	G15360	Carbon Steel, Wrought–Medium Carbon
1541	G15410	Carbon Steel, Wrought–Medium Carbon
1547	G15470	Carbon Steel, Wrought–Medium Carbon
1548	G15480	Carbon Steel, Wrought–Medium Carbon
1551	G15510	Carbon Steel, Wrought–Medium Carbon
1552	G15520	Carbon Steel, Wrought–Medium Carbon
1561	G15610	Carbon Steel, Wrought–High Carbon
1566	G15660	Carbon Steel, Wrought–High Carbon
1572	G15720	Carbon Steel, Wrought–High Carbon
2011	A92011	Aluminum Alloy, Wrought
2014	A92014	Aluminum Alloy, Wrought
2017	A92017	Aluminum Alloy, Wrought
2018	A92018	Aluminum Alloy, Wrought
2021	A92021	Aluminum Alloy, Wrought
2024	A92024	Aluminum Alloy, Wrought
2025	A92025	Aluminum Alloy, Wrought
2117	A92117	Aluminum Alloy, Wrought
2218	A92218	Aluminum Alloy, Wrought
2219	A92219	Aluminum Alloy, Wrought
2315		Alloy Steel, Cast–Low Carbon
2320		Alloy Steel, Cast–Low Carbon
2325		Alloy Steel, Cast–Medium Carbon
2330		Alloy Steel, Cast–Medium Carbon
2618	A92618	Aluminum Alloy, Wrought
3003	A93003	Aluminum Alloy, Wrought
3004	A93004	Aluminum Alloy, Wrought
3005	A93005	Aluminum Alloy, Wrought
4012	G40120	Alloy Steel, Wrought–Low Carbon
4023	G40230	Alloy Steel, Wrought–Low Carbon
4024	G40240	Alloy Steel, Wrought–Low Carbon
4027	G40270	Alloy Steel, Wrought–Medium Carbon
4028	G40280	Alloy Steel, Wrought–Medium Carbon
4032	G40320	Alloy Steel, Wrought–Medium Carbon
4032	A94032	Aluminum Alloy, Wrought
4037	G40370	Alloy Steel, Wrought–Medium Carbon
4042	G40420	Alloy Steel, Wrought–Medium Carbon
4047	G40470	Alloy Steel, Wrought–Medium Carbon
4110		Alloy Steel, Cast–Low Carbon
4118	G41180	Alloy Steel, Wrought–Low Carbon
4120		Alloy Steel, Cast–Low Carbon
4125		Alloy Steel, Cast–Medium Carbon
4130	G41300	Alloy Steel, Wrought–Medium Carbon
4130	J13408	Alloy Steel, Cast–Medium Carbon
41L30		Free Machining Alloy Steel, Wrought–Medium Carbon Leaded
4135	G41350	Alloy Steel, Wrought–Medium Carbon
4137	G41370	Alloy Steel, Wrought–Medium Carbon
4140	G41400	Alloy Steel, Wrought–Medium Carbon
4140	J14047	Alloy Steel, Cast–Medium Carbon
4140		Free Machining Alloy Steel, Wrought–Medium Carbon Resulfurized
4140Se		Free Machining Alloy Steel, Wrought–Medium Carbon Resulfurized
41L40		Free Machining Alloy Steel, Wrought–Medium Carbon Leaded

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
4142	G41420	Alloy Steel, Wrought–Medium Carbon
4142Te		Free Machining Alloy Steel, Wrought–Medium Carbon Resulfurized
4145	G41450	Alloy Steel, Wrought–Medium Carbon
4145Se		Free Machining Alloy Steel, Wrought–Medium Carbon Resulfurized
41L45		Free Machining Alloy Steel, Wrought–Medium and High Carbon Leaded
4147	G41470	Alloy Steel, Wrought–Medium Carbon
4147Te		Free Machining Alloy Steel, Wrought–Medium Carbon Resulfurized
41L47		Free Machining Alloy Steel, Wrought–Medium Carbon Leaded
4150	G41500	Alloy Steel, Wrought–Medium Carbon
4150		Free Machining Alloy Steel, Wrought–Medium Carbon Resulfurized
41L50		Free Machining Alloy Steel, Wrought–Medium Carbon Leaded
4161	G41610	Alloy Steel, Wrought–Medium Carbon
4320	G43200	Alloy Steel, Wrought–Low Carbon
4320		Alloy Steel, Cast–Low Carbon
4330		Alloy Steel, Cast–Medium Carbon
4330V	K23080	High Strength Steel, Wrought
4340	G43400	Alloy Steel, Wrought–Medium Carbon
4340	J24055	Alloy Steel, Cast–Medium Carbon
4340		High Strength Steel, Wrought
4340Si	J24060	High Strength Steel, Wrought
43L40		Free Machining Alloy Steel, Wrought–Medium and High Carbon Leaded
4419	G44190	Alloy Steel, Wrought–Low Carbon
4422	G44220	Alloy Steel, Wrought–Low Carbon
4427	G44270	Alloy Steel, Wrought–Medium Carbon
4615	G46150	Alloy Steel, Wrought–Low Carbon
4617	G46170	Alloy Steel, Wrought–Low Carbon
4620	G46200	Alloy Steel, Wrought–Low Carbon
4621	G46210	Alloy Steel, Wrought–Low Carbon
4626	G46260	Alloy Steel, Wrought–Medium Carbon
4718	G47180	Alloy Steel, Wrought–Low Carbon
4720	G47200	Alloy Steel, Wrought–Low Carbon
4815	G48150	Alloy Steel, Wrought–Low Carbon
4817	G48170	Alloy Steel, Wrought–Low Carbon
4820	G48200	Alloy Steel, Wrought–Low Carbon
5005	A95005	Aluminum Alloy, Wrought
5015	G50150	Alloy Steel, Wrought–Low Carbon
50B40	G50401	Alloy Steel, Wrought–Medium Carbon
50B44	G50441	Alloy Steel, Wrought–Medium Carbon
5046	G50460	Alloy Steel, Wrought–Medium Carbon
50B46	G50461	Alloy Steel, Wrought–Medium Carbon
5050	A95050	Aluminum Alloy, Wrought
50B50	G50501	Alloy Steel, Wrought–Medium Carbon
5052	A95052	Aluminum Alloy, Wrought
5056	A95056	Aluminum Alloy, Wrought
5060	G50600	Alloy Steel, Wrought–Medium Carbon
50B60	G50601	Alloy Steel, Wrought–Medium Carbon
5083	A95083	Aluminum Alloy, Wrought
5086	A95086	Aluminum Alloy, Wrought
5115	G51150	Alloy Steel, Wrought–Low Carbon
5120	G51200	Alloy Steel, Wrought–Low Carbon
5130	G51300	Alloy Steel, Wrought–Medium Carbon
5132	G51320	Alloy Steel, Wrought–Medium Carbon

26.1 Numerical List of Materials

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
51L32		Free Machining Alloy Steel, Wrought–Medium Carbon Leaded
5135	G51350	Alloy Steel, Wrought–Medium Carbon
5140	G51400	Alloy Steel, Wrought–Medium Carbon
5145	G51450	Alloy Steel, Wrought–Medium Carbon
5147	G51470	Alloy Steel, Wrought–Medium Carbon
5150	G51500	Alloy Steel, Wrought–Medium Carbon
5154	A95154	Aluminum Alloy, Wrought
5155	G51550	Alloy Steel, Wrought–Medium Carbon
5160	G51600	Alloy Steel, Wrought–Medium Carbon
51B60	G51601	Alloy Steel, Wrought–Medium Carbon
5252	A95252	Aluminum Alloy, Wrought
5254	A95254	Aluminum Alloy, Wrought
5454	A95454	Aluminum Alloy, Wrought
5456	A95456	Aluminum Alloy, Wrought
5457	A95457	Aluminum Alloy, Wrought
5652	A95652	Aluminum Alloy, Wrought
5657	A95657	Aluminum Alloy, Wrought
6053	A96053	Aluminum Alloy, Wrought
6061	A96061	Aluminum Alloy, Wrought
6063	A96063	Aluminum Alloy, Wrought
6066	A96066	Aluminum Alloy, Wrought
6070	A96070	Aluminum Alloy, Wrought
6101	A96101	Aluminum Alloy, Wrought
6118	G61180	Alloy Steel, Wrought–Low Carbon
6150	G61500	Alloy Steel, Wrought–Medium Carbon
6151	A96151	Aluminum Alloy, Wrought
6253	A96253	Aluminum Alloy, Wrought
6262	A96262	Aluminum Alloy, Wrought
6463	A96463	Aluminum Alloy, Wrought
6951	A96951	Aluminum Alloy, Wrought
7001	A97001	Aluminum Alloy, Wrought
7004	A97004	Aluminum Alloy, Wrought
7005	A97005	Aluminum Alloy, Wrought
7039	A97039	Aluminum Alloy, Wrought
7049	A97049	Aluminum Alloy, Wrought
7050	A97050	Aluminum Alloy, Wrought
7075	A97075	Aluminum Alloy, Wrought
7079	A97079	Aluminum Alloy, Wrought
7175	A97175	Aluminum Alloy, Wrought
7178	A97178	Aluminum Alloy, Wrought
8020		Alloy Steel, Cast–Low Carbon
8030		Alloy Steel, Cast–Medium Carbon
80B30		Alloy Steel, Cast–Medium Carbon
8040		Alloy Steel, Cast–Medium Carbon
8115	G81150	Alloy Steel, Wrought–Low Carbon
81B45	G81451	Alloy Steel, Wrought–Medium Carbon
8430		Alloy Steel, Cast–Medium Carbon
8440		Alloy Steel, Cast–Medium Carbon
8617	G86170	Alloy Steel, Wrought–Low Carbon
8620	G86200	Alloy Steel, Wrought–Low Carbon
8620		Alloy Steel, Cast–Low Carbon
86L20		Free Machining Alloy Steel, Wrought–Medium Carbon Leaded

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
8622	G86220	Alloy Steel, Wrought–Low Carbon
8625	G86250	Alloy Steel, Wrought–Medium Carbon
8627	G86270	Alloy Steel, Wrought–Medium Carbon
8630	G86300	Alloy Steel, Wrought–Medium Carbon
8630		Alloy Steel, Cast–Medium Carbon
8637	G86370	Alloy Steel, Wrought–Medium Carbon
8640	G86400	Alloy Steel, Wrought–Medium Carbon
8640		Alloy Steel, Cast–Medium Carbon
86L40		Free Machining Alloy Steel, Wrought–Medium Carbon Leaded
8642	G86420	Alloy Steel, Wrought–Medium Carbon
8645	G86450	Alloy Steel, Wrought–Medium Carbon
86B45	G86451	Alloy Steel, Wrought–Medium Carbon
8650	G86500	Alloy Steel, Wrought–Medium Carbon
8655	G86550	Alloy Steel, Wrought–Medium Carbon
8660	G86600	Alloy Steel, Wrought–Medium Carbon
8740	G87400	Alloy Steel, Wrought–Medium Carbon
8742	G87420	Alloy Steel, Wrought–Medium Carbon
8822	G88220	Alloy Steel, Wrought–Low Carbon
9254	G92540	Alloy Steel, Wrought–Medium Carbon
9255	G92550	Alloy Steel, Wrought–Medium Carbon
9260	G92600	Alloy Steel, Wrought–Medium Carbon
9310	G93106	Alloy Steel, Wrought–Low Carbon
94B15	G94151	Alloy Steel, Wrought–Low Carbon
94B17	G94171	Alloy Steel, Wrought–Low Carbon
94B30	G94301	Alloy Steel, Wrought–Medium Carbon
9525		Alloy Steel, Cast–Medium Carbon
9530		Alloy Steel, Cast–Medium Carbon
9535		Alloy Steel, Cast–Medium Carbon
98BV40		High Strength Steel, Wrought
50100	G50986	Alloy Steel, Wrought–High Carbon
51100	G51986	Alloy Steel, Wrought–High Carbon
52100	G52986	Alloy Steel, Wrought–High Carbon
52L100		Free Machining Alloy Steel, Wrought–High Carbon Leaded

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Alphabetical List of Materials 26.2

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
A2	T30102	Tool Steel, Wrought—Cold Work
A3	T30103	Tool Steel, Wrought—Cold Work
A4	T30104	Tool Steel, Wrought—Cold Work
A6	T30106	Tool Steel, Wrought—Cold Work
A7	T30107	Tool Steel, Wrought—Cold Work
A8	T30108	Tool Steel, Wrought—Cold Work
A9	T30109	Tool Steel, Wrought—Cold Work
A10	T30110	Tool Steel, Wrought—Cold Work
A140		Aluminum Alloy, Cast—Sand Cast
A-286	K66286	High Temperature Alloy—Iron Base, Wrought
A332.0	A13320	Aluminum Alloy, Cast—Permanent Mold Cast
A356.0	A13560	Aluminum Alloy, Cast—Sand and Permanent Mold Cast
A360.0	A13600	Aluminum Alloy, Cast—Die Casting
A380.0	A13800	Aluminum Alloy, Cast—Die Casting
A384.0	A03840	Aluminum Alloy, Cast—Die Casting
A413.0	A14130	Aluminum Alloy, Cast—Die Casting
A514.0	A15140	Aluminum Alloy, Cast—Permanent Mold Cast
A712.0	A17120	Aluminum Alloy, Cast—Sand Cast
A850.0	A18500	Aluminum Alloy, Cast—Sand and Permanent Mold Cast
ABS		Plastic—Thermoplastic
AC41A	Z35531	Zinc Alloy, Cast
Acetal		Plastic—Thermoplastic
ACI Grade CB-7Cu	J92170	Precipitation Hardening Stainless Steel, Cast
ACI Grade CD-4MCu	J93370	Precipitation Hardening Stainless Steel, Cast
Acrylic		Plastic—Thermoplastic
Acrylonitrile-Butadiene-Styrene		Plastic—Thermoplastic
AF2-1DA		High Temperature Alloy—Nickel Base, Wrought
AF-71		Precipitation Hardening Stainless Steel, Wrought
AFC-77	K65770	Precipitation Hardening Stainless Steel, Wrought
AG40A	Z33520	Zinc Alloy, Cast
AiResist 13		High Temperature Alloy—Cobalt Base, Cast
AiResist 213		High Temperature Alloy—Cobalt Base, Wrought
AiResist 215		High Temperature Alloy—Cobalt Base, Cast
Al-1Mg-0.6Si-0.25Cu		Powder Metal Alloy—Aluminum Alloy
Al-0.6Mg-0.4Si		Powder Metal Alloy—Aluminum Alloy
Al-4.4Cu-0.8Si-0.4Mg		Powder Metal Alloy—Aluminum Alloy
Allyl (DAP)		Plastic—Thermosetting Plastic
Allyl-Glass filled		Plastic—Thermosetting Plastic
Allyl-Fiber filled		Plastic—Thermosetting Plastic
Almar 362	S36200	Precipitation Hardening Stainless Steel, Wrought
Alnico I		Magnetic Alloy
Alnico II		Magnetic Alloy
Alnico III		Magnetic Alloy
Alnico IV		Magnetic Alloy
Alnico V		Magnetic Alloy
Alnico V-7		Magnetic Alloy
Alnico XII		Magnetic Alloy
Alumina		Glasses & Ceramics—Ceramic
Alumina (Pure)		Flame (Thermal) Sprayed Material—Inorganic Coating Material
Alumina (Grey) containing Titania		Flame (Thermal) Sprayed Material—Inorganic Coating Material

26.2 Alphabetical List of Materials

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
Alumina, Nickel Aluminide Blends		Flame (Thermal) Sprayed Material–Inorganic Coating Material
Alumina-Mullite		Glasses & Ceramics–Ceramic
Aluminum Alloys		Flame (Thermal) Sprayed Material
Aluminum Oxide		Glasses & Ceramics–Ceramic
Aluminum Silicate		Glasses & Ceramics–Ceramic
AM60A	M10600	Magnesium Alloy, Cast
AM100A	M10100	Magnesium Alloy, Cast
AM-350	S35000	Precipitation Hardening Stainless Steel, Wrought
AM-355	S35500	Precipitation Hardening Stainless Steel, Wrought
AM-355	S35500	Precipitation Hardening Stainless Steel, Cast
AM-362	S36200	Precipitation Hardening Stainless Steel, Wrought
AM-363		Precipitation Hardening Stainless Steel, Wrought
AMS 4803	Z33520	Zinc Alloy, Cast
Anviloy 1100		Refractory Alloy, Cast, P/M–Tungsten Alloy
Anviloy 1150		Refractory Alloy, Cast, P/M–Tungsten Alloy
Anviloy 1200		Refractory Alloy, Cast, P/M–Tungsten Alloy
AS41A	M10410	Magnesium Alloy, Cast
ASTAR 811C		Refractory Alloy, Wrought, Cast, P/M–Tantalum
ASTM A27:		
Grade N1	J02500	Alloy Steel, Cast–Medium Carbon
Grade N2	J03500	Alloy Steel, Cast–Medium Carbon
Grade U-60-30	J02500	Alloy Steel, Cast–Medium Carbon
Grade 60-30	J03000	Alloy Steel, Cast–Medium Carbon
Grade 65-35	J03001	Alloy Steel, Cast–Medium Carbon
Grade 70-36	J03501	Alloy Steel, Cast–Medium Carbon
Grade 70-40	J02501	Alloy Steel, Cast–Medium Carbon
ASTM A47:		
Grade 32510	F22200	Malleable Cast Iron–Ferritic
Grade 35018	F22400	Malleable Cast Iron–Ferritic
ASTM A48:		
Class 20	F11401	Gray Cast Iron–Ferritic
Class 25	F11701	Gray Cast Iron–Pearlitic-Ferritic
Class 30	F12101	Gray Cast Iron–Pearlitic
Class 35	F12401	Gray Cast Iron–Pearlitic
Class 40	F12801	Gray Cast Iron–Pearlitic
Class 45	F13101	Gray Cast Iron–Pearlitic + Free Carbides
Class 50	F13501	Gray Cast Iron–Pearlitic + Free Carbides
Class 55	F13801	Gray Cast Iron–Pearlitic or Acicular + Free Carbides
Class 60	F14101	Gray Cast Iron–Pearlitic or Acicular + Free Carbides
ASTM A128:		
Grade A	J91101	Austenitic Manganese Steel, Cast
Grade B-1	J91119	Austenitic Manganese Steel, Cast
Grade B-2	J91129	Austenitic Manganese Steel, Cast
Grade B-3	J91139	Austenitic Manganese Steel, Cast
Grade B-4	J91149	Austenitic Manganese Steel, Cast
Grade C	J91309	Austenitic Manganese Steel, Cast
Grade D	J91459	Austenitic Manganese Steel, Cast
Grade E-1	J91249	Austenitic Manganese Steel, Cast
Grade E-2	J91339	Austenitic Manganese Steel, Cast
Grade F	J69990	Austenitic Manganese Steel, Cast

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
ASTM A148:		
Grade 80-40	D50400	Alloy Steel, Cast–Medium Carbon
Grade 80-50	D50500	Alloy Steel, Cast–Medium Carbon
Grade 90-60	D50600	Alloy Steel, Cast–Medium Carbon
Grade 105-85	D50850	Alloy Steel, Cast–Medium Carbon
Grade 120-95	D50950	Alloy Steel, Cast–Medium Carbon
Grade 150-125	D51250	Alloy Steel, Cast–Medium Carbon
Grade 175-145	D51450	Alloy Steel, Cast–Medium Carbon
ASTM A216:		
Grade WCA	J02502	Alloy Steel, Cast–Medium Carbon
Grade WCB	J03002	Alloy Steel, Cast–Medium Carbon
Grade WCC	J02503	Alloy Steel, Cast–Medium Carbon
ASTM A217:		
Grade C5	J42045	Stainless Steel, Cast–Ferritic
Grade C12	J82090	Stainless Steel, Cast–Ferritic
Grade CA-15	J91150	Stainless Steel, Cast–Martensitic
Grade WC1	J12522	Alloy Steel, Cast–Medium Carbon
Grade WC4	J12082	Alloy Steel, Cast–Medium Carbon
Grade WC5	J22000	Alloy Steel, Cast–Medium Carbon
Grade WC6	J12072	Alloy Steel, Cast–Medium Carbon
Grade WC9	J21890	Alloy Steel, Cast–Low Carbon
ASTM A220:		
Grade 40010	F22830	Malleable Cast Iron–Pearlitic
Grade 45006	F23131	Malleable Cast Iron–Pearlitic
Grade 45008	F23130	Malleable Cast Iron–Pearlitic
Grade 50005	F23530	Malleable Cast Iron–Pearlitic
Grade 60004	F24130	Malleable Cast Iron–Tempered Martensite
Grade 70003	F24830	Malleable Cast Iron–Tempered Martensite
Grade 80002	F25530	Malleable Cast Iron–Tempered Martensite
Grade 90001	F26230	Malleable Cast Iron–Tempered Martensite
ASTM A296:		
Grade CA6N	J91650	Stainless Steel, Cast–Ferritic
Grade CA-6NM	J91540	Stainless Steel, Cast–Ferritic
Grade CA-15	J91150	Stainless Steel, Cast–Martensitic
Grade CA15M	J91151	Stainless Steel, Cast–Martensitic
Grade CA-40	J91153	Stainless Steel, Cast–Martensitic
Grade CB-30	J91803	Stainless Steel, Cast–Ferritic
Grade CC-50	J92615	Stainless Steel, Cast–Ferritic
Grade CD4MCu	J93370	Stainless Steel, Cast–Ferritic
Grade CE-30	J93423	Stainless Steel, Cast–Ferritic
Grade CF-3	J92700	Stainless Steel, Cast–Austenitic
Grade CF-3M	J92800	Stainless Steel, Cast–Austenitic
Grade CF-8	J92600	Stainless Steel, Cast–Austenitic
Grade CF-8C	J92710	Stainless Steel, Cast–Austenitic
Grade CF-8M	J92900	Stainless Steel, Cast–Austenitic
Grade CF-16F	J92701	Stainless Steel, Cast–Austenitic
Grade CF-20	J92602	Stainless Steel, Cast–Austenitic
Grade CG-8M	J93000	Stainless Steel, Cast–Austenitic
Grade CG-12	J93001	Stainless Steel, Cast–Austenitic
Grade CH-20	J93402	Stainless Steel, Cast–Austenitic
Grade CK-20	J94202	Stainless Steel, Cast–Austenitic

26.2 Alphabetical List of Materials

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
ASTM A296 *(continued)*		
Grade CN-7M	J95150	Stainless Steel. Cast–Austenitic
Grade CN-7MS	J94650	Stainless Steel. Cast–Austenitic
Grade CW-12M		High Temperature Alloy–Nickel Base. Cast
Grade CY-40	N07750	High Temperature Alloy–Nickel Base. Cast
Grade CZ-100	N02100	Nickel Alloy. Cast
Grade M-35		Nickel Alloy. Cast
Grade N-12M		High Temperature Alloy–Nickel Base. Cast
ASTM A297:		
Grade HC	J92605	Stainless Steel. Cast–Ferritic
Grade HD	J93005	Stainless Steel. Cast–Austenitic
Grade HE	J93403	Stainless Steel. Cast–Austenitic
Grade HF	J92603	Stainless Steel. Cast–Austenitic
Grade HH	J93503	Stainless Steel. Cast–Austenitic
Grade HI	J94003	Stainless Steel. Cast–Austenitic
Grade HK	J94224	Stainless Steel. Cast–Austenitic
Grade HL	J94604	Stainless Steel. Cast–Austenitic
Grade HN	J94213	Stainless Steel. Cast–Austenitic
Grade HP	J95705	Stainless Steel. Cast–Austenitic
Grade HT	J94605	Stainless Steel. Cast–Austenitic
Grade HU	J95405	Stainless Steel. Cast–Austenitic
Grade HW	N08001	High Temperature Alloy–Nickel Base. Cast
Grade HX	N06006	High Temperature Alloy–Nickel Base. Cast
ASTM A351:		
Grade CD-4MCu	J93370	Precipitation Hardening Stainless Steel. Cast
Grade CF-3	J92500	Stainless Steel. Cast–Austenitic
Grade CF-3A	J92500	Stainless Steel. Cast–Austenitic
Grade CF-3M	J92800	Stainless Steel. Cast–Austenitic
Grade CF-3MA	J92800	Stainless Steel. Cast–Austenitic
Grade CF-8	J92600	Stainless Steel. Cast–Austenitic
Grade CF-8A		Stainless Steel. Cast–Austenitic
Grade CF-8C	J92710	Stainless Steel. Cast–Austenitic
Grade CF-8M	J92900	Stainless Steel. Cast–Austenitic
Grade CF-10MC	J92971	Stainless Steel. Cast–Austenitic
Grade CH-6	J93400	Stainless Steel. Cast–Austenitic
Grade CH-10	J93401	Stainless Steel. Cast–Austenitic
Grade CH-20	J93402	Stainless Steel. Cast–Austenitic
Grade CK-20	J94202	Stainless Steel. Cast–Austenitic
Grade CN-7M	J95150	Stainless Steel. Cast–Austenitic
Grade HK-30	J94203	Stainless Steel. Cast–Austenitic
Grade HK-40	J94204	Stainless Steel. Cast–Austenitic
Grade HT-30	J94603	Stainless Steel. Cast–Austenitic
ASTM A352:		
Grade LC1	J12522	Alloy Steel. Cast–Medium Carbon
Grade LC2	J22500	Alloy Steel. Cast–Medium Carbon
Grade LC2-1	J42215	Alloy Steel. Cast–Medium Carbon
Grade LC3	J31550	Alloy Steel. Cast–Low Carbon
Grade LC4	J41500	Alloy Steel. Cast–Low Carbon
Grade LCA	J02504	Carbon Steel. Cast–Medium Carbon
Grade LCB	J03003	Carbon Steel. Cast–Medium Carbon
Grade LCC	J02505	Carbon Steel. Cast–Medium Carbon

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
ASTM A356:		
Grade 1	J03502	Carbon Steel, Cast–Medium Carbon
Grade 2	J12523	Alloy Steel, Cast–Medium Carbon
Grade 5	J12540	Alloy Steel, Cast–Medium Carbon
Grade 6	J12073	Alloy Steel, Cast–Medium Carbon
Grade 8	J11691	Alloy Steel, Cast–Medium Carbon
Grade 9	J21610	Alloy Steel, Cast–Medium Carbon
Grade 10	J22090	Alloy Steel, Cast–Medium Carbon
ASTM A369:		
Grade FPA	K02501	Carbon and Ferritic Alloy Steel (High Temperature Service)
Grade FPB	K03006	Carbon and Ferritic Alloy Steel (High Temperature Service)
Grade FP1	K11522	Carbon and Ferritic Alloy Steel (High Temperature Service)
Grade FP2	K11547	Carbon and Ferritic Alloy Steel (High Temperature Service)
Grade FP3b	K21509	Carbon and Ferritic Alloy Steel (High Temperature Service)
Grade FP5	K41545	Carbon and Ferritic Alloy Steel (High Temperature Service)
Grade FP7	K61595	Carbon and Ferritic Alloy Steel (High Temperature Service)
Grade FP9	K90941	Carbon and Ferritic Alloy Steel (High Temperature Service)
Grade FP11	K11597	Carbon and Ferritic Alloy Steel (High Temperature Service)
Grade FP12	K11562	Carbon and Ferritic Alloy Steel (High Temperature Service)
Grade FP21	K31545	Carbon and Ferritic Alloy Steel (High Temperature Service)
Grade FP22	K21590	Carbon and Ferritic Alloy Steel (High Temperature Service)
ASTM A389:		
Grade C23	J12080	Alloy Steel, Cast–Medium Carbon
Grade C24	J12092	Alloy Steel, Cast–Medium Carbon
ASTM A426:		
Grade CP1	J02508	Carbon Steel, Cast–Low Carbon
Grade CP2	J11542	Alloy Steel, Cast–Low Carbon
Grade CP5	J42045	Alloy Steel, Cast–Low Carbon
Grade CP5b	J41545	Alloy Steel, Cast–Low Carbon
Grade CP7	J61544	Stainless Steel, Cast–Martensitic
Grade CP9	J82091	Stainless Steel, Cast–Martensitic
Grade CP11	J12073	Alloy Steel, Cast–Low Carbon
Grade CP12	J11562	Alloy Steel, Cast–Low Carbon
Grade CP15	J11522	Alloy Steel, Cast–Low Carbon
Grade CP21	J31545	Alloy Steel, Cast–Low Carbon
Grade CP22	J21891	Alloy Steel, Cast–Low Carbon
Grade CPCA15	J91151	Stainless Steel, Cast–Martensitic
ASTM A436:		
Type 1	F41000	Gray Cast Iron–Austenitic (NI-RESIST)
Type 1b	F41001	Gray Cast Iron–Austenitic (NI-RESIST)
Type 2	F41002	Gray Cast Iron–Austenitic (NI-RESIST)
Type 2b	F41003	Gray Cast Iron–Austenitic (NI-RESIST)
Type 3	F41004	Gray Cast Iron–Austenitic (NI-RESIST)
Type 4	F41005	Gray Cast Iron–Austenitic (NI-RESIST)
Type 5	F41006	Gray Cast Iron–Austenitic (NI-RESIST)
Type 6	F41007	Gray Cast Iron–Austenitic (NI-RESIST)
ASTM A439:		
Type D-2	F43000	Ductile Cast Iron–Austenitic (NI-RESIST Ductile)
Type D-2B	F43001	Ductile Cast Iron–Austenitic (NI-RESIST Ductile)
Type D-2C	F43002	Ductile Cast Iron–Austenitic (NI-RESIST Ductile)
Type D-3	F43003	Ductile Cast Iron–Austenitic (NI-RESIST Ductile)

26.2 Alphabetical List of Materials

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
ASTM A439 *(continued)*		
Type D-3A	F43004	Ductile Cast Iron–Austenitic (NI-RESIST Ductile)
Type D-4	F43005	Ductile Cast Iron–Austenitic (NI-RESIST Ductile)
Type D-5	F43006	Ductile Cast Iron–Austenitic (NI-RESIST Ductile)
Type D-5B	F43007	Ductile Cast Iron–Austenitic (NI-RESIST Ductile)
ASTM A451:		
Grade CPF3		Stainless Steel, Cast–Austenitic
Grade CPF3A		Stainless Steel, Cast–Austenitic
Grade CPF3M		Stainless Steel, Cast–Austenitic
Grade CPF8		Stainless Steel, Cast–Austenitic
Grade CPF8A	J92600	Stainless Steel, Cast–Austenitic
Grade CPF8C	J92710	Stainless Steel, Cast–Austenitic
Grade CPF8C (Ta Max.)	J92710	Stainless Steel, Cast–Austenitic
Grade CPF8M	J92900	Stainless Steel, Cast–Austenitic
Grade CPF10MC	J92971	Stainless Steel, Cast–Austenitic
Grade CPH8	J93400	Stainless Steel, Cast–Austenitic
Grade CPH10	J93402	Stainless Steel, Cast–Austenitic
Grade CPH20	J93402	Stainless Steel, Cast–Austenitic
Grade CPK20	J94202	Stainless Steel, Cast–Austenitic
ASTM A452:		
Grade TP 304H	S30409	Stainless Steel, Cast–Austenitic
Grade TP 316H	S31609	Stainless Steel, Cast–Austenitic
Grade TP 347H	S31709	Stainless Steel, Cast–Austenitic
ASTM A486:		
Class 70	J03503	Alloy Steel, Cast–Medium Carbon
Class 90	J03504	Alloy Steel, Cast–Medium Carbon
Class 120	J03504	Alloy Steel, Cast–Medium Carbon
ASTM A487:		
Class 1N	J03004	Alloy Steel, Cast–Medium Carbon
Class 2N	J13005	Alloy Steel, Cast–Medium Carbon
Class 4N	J13047	Alloy Steel, Cast–Medium Carbon
Class 6N	J13855	Alloy Steel, Cast–Medium Carbon
Class 8N	J22091	Alloy Steel, Cast–Medium Carbon
Class 9N	J13345	Alloy Steel, Cast–Medium Carbon
Class 10N	J23015	Alloy Steel, Cast–Medium Carbon
Class 1Q	J03004	Alloy Steel, Cast–Medium Carbon
Class 2Q	J13005	Alloy Steel, Cast–Medium Carbon
Class 4Q	J13047	Alloy Steel, Cast–Medium Carbon
Class 4QA	J13047	Alloy Steel, Cast–Medium Carbon
Class 6Q	J13855	Alloy Steel, Cast–Medium Carbon
Class 7Q	J12084	Alloy Steel, Cast–Medium Carbon
Class 8Q	J22091	Alloy Steel, Cast–Medium Carbon
Class 9Q	J13345	Alloy Steel, Cast–Medium Carbon
Class 10Q	J23015	Alloy Steel, Cast–Medium Carbon
Class CA6NM	J91540	Stainless Steel, Cast–Ferritic
Class CA15a	J91150	Stainless Steel, Cast–Martensitic
Class CA15M	J91151	Stainless Steel, Cast–Martensitic
Class DN	J04500	Alloy Steel, Cast–Medium Carbon
ASTM A494:		
Grade CW-12M-1	N10002	High Temperature Alloy–Nickel Base, Cast
Grade CW-12M-2	N10002	High Temperature Alloy–Nickel Base, Cast
Grade CZ-100	N02100	Nickel Alloy, Wrought and Cast

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
Grade CY-40	N07750	High Temperature Alloy–Nickel Base, Cast
Grade M-35		Nickel Alloy, Wrought and Cast
Grade N-12M-1	N10001	High Temperature Alloy–Nickel Base, Cast
Grade N-12M-2	N10001	High Temperature Alloy–Nickel Base, Cast
ASTM A518	F47003	High Silicon Cast Iron
ASTM A532:		
Class I, Type A	F45000	White Cast Iron (Abrasion Resistant)
Class I, Type B	F45001	White Cast Iron (Abrasion Resistant)
Class I, Type C	F45002	White Cast Iron (Abrasion Resistant)
Class I, Type D	F45003	White Cast Iron (Abrasion Resistant)
Class II, Type A	F45004	White Cast Iron (Abrasion Resistant)
Class II, Type B	F45005	White Cast Iron (Abrasion Resistant)
Class II, Type C	F45006	White Cast Iron (Abrasion Resistant)
Class II, Type D	F45007	White Cast Iron (Abrasion Resistant)
Class II, Type E	F45008	White Cast Iron (Abrasion Resistant)
Class III, Type A	F45009	White Cast Iron (Abrasion Resistant)
ASTM A536:		
Grade 60-40-18	F32800	Ductile Cast Iron–Ferritic
Grade 65-45-12	F33100	Ductile Cast Iron–Ferritic
Grade 80-55-06	F33800	Ductile Cast Iron–Ferritic-Pearlitic
Grade 100-70-03	F34800	Ductile Cast Iron–Pearlitic-Martensitic
Grade 120-90-02	F36200	Ductile Cast Iron–Martensitic
ASTM A538:		
Grade A		Maraging Steel, Wrought
Grade B		Maraging Steel, Wrought
Grade C		Maraging Steel, Wrought
ASTM A560.		
Grade 50Cr-50Ni	R20500	Chromium-Nickel Alloy Casting
Grade 60Cr-40Ni	R20600	Chromium-Nickel Alloy Casting
ASTM A571.		
Type D-2M	F43010	Ductile Cast Iron–Austenitic (NI-RESIST Ductile)
ASTM A597:		
Grade CA-2	T90102	Tool Steel, Cast–Cold Work
Grade CD-2	T90402	Tool Steel, Cast–Cold Work
Grade CD-5	T90405	Tool Steel, Cast–Cold Work
Grade CH-12	T90812	Tool Steel, Cast–Hot Work
Grade CH-13	T90813	Tool Steel, Cast–Hot Work
Grade CO-1	T91501	Tool Steel, Cast–Cold Work
Grade CS-5	T91905	Tool Steel, Cast–Shock Resisting
ASTM A602:		
Grade M3210	F20000	Malleable Cast Iron–Ferritic
Grade M4504	F20001	Malleable Cast Iron–Pearlitic
Grade M5003	F20002	Malleable Cast Iron–Pearlitic
Grade M5503	F20003	Malleable Cast Iron–Tempered Martensite
Grade M7002	F20004	Malleable Cast Iron–Tempered Martensite
Grade M8501	F20005	Malleable Cast Iron–Tempered Martensite
ASTM A608:		
Grade HC30	J92613	Stainless Steel, Cast–Ferritic
Grade HD50	J93015	Stainless Steel, Cast–Austenitic
Grade HE35	J93413	Stainless Steel, Cast–Austenitic
Grade HF30	J92803	Stainless Steel, Cast–Austenitic
Grade HH30	J93513	Stainless Steel, Cast–Austenitic

26.2 Alphabetical List of Materials

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
ASTM A608 *(continued)*		
Grade HH33	J93633	Stainless Steel, Cast–Austenitic
Grade HI35	J94013	Stainless Steel, Cast–Austenitic
Grade HK30	J94203	Stainless Steel, Cast–Austenitic
Grade HK40	J94204	Stainless Steel, Cast–Austenitic
Grade HL30	J94613	Stainless Steel, Cast–Austenitic
Grade HL40	J94614	Stainless Steel, Cast–Austenitic
Grade HN40	J94214	Stainless Steel, Cast–Austenitic
Grade HT50	J94805	Stainless Steel, Cast–Austenitic
Grade HU50	J95404	Stainless Steel, Cast–Austenitic
Grade HW50	N08005	High Temperature Alloy–Nickel Base, Cast
Grade HX50	N06050	High Temperature Alloy–Nickel Base, Cast
ASTM B23:		
Alloy 1	L13910	Tin Alloy, Cast–Tin Babbit Alloy
Alloy 2	L13890	Tin Alloy, Cast–Tin Babbit Alloy
Alloy 3	L13840	Tin Alloy, Cast–Tin Babbit Alloy
Alloy 7	L05237	Lead Alloy, Cast–Lead Babbit Alloy
Alloy 8	L05188	Lead Alloy, Cast–Lead Babbit Alloy
Alloy 11	L13870	Tin Alloy, Cast–Tin Babbit Alloy
Alloy 13	L05153	Lead Alloy, Cast–Lead Babbit Alloy
Alloy 15	L05155	Lead Alloy, Cast–Lead Babbit Alloy
ASTM B367:		
Grade C-1	R50250	Titanium Alloy, Cast–Commercially Pure
Grade C-2	R50400	Titanium Alloy, Cast–Commercially Pure
Grade C-3	R50550	Titanium Alloy, Cast–Commercially Pure
Grade C-4	R50700	Titanium Alloy, Cast–Commercially Pure
Grade C-5	R56400	Titanium Alloy, Cast–Alpha and Alpha-Beta Alloy
Grade C-6	R54520	Titanium Alloy, Cast–Alpha and Alpha-Beta Alloy
Grade C-7A	R52250	Titanium Alloy Cast–Commercially Pure
Grade C-7B	R52400	Titanium Alloy, Cast–Commercially Pure
Grade C-8A	R52550	Titanium Alloy, Cast–Commercially Pure
Grade C-8B		Titanium Alloy, Cast–Commercially Pure
Astroloy		High Temperature Alloy–Nickel Base, Wrought
AZ21A	M11210	Magnesium Alloy, Wrought
AZ31B	M11311	Magnesium Alloy, Wrought
AZ31C	M11312	Magnesium Alloy, Wrought
AZ61A	M11610	Magnesium Alloy, Wrought
AZ63A	M11630	Magnesium Alloy, Cast
AZ80A	M11800	Magnesium Alloy, Wrought
AZ81A	M11810	Magnesium Alloy, Cast
AZ91A	M11910	Magnesium Alloy, Cast
AZ91B	M11912	Magnesium Alloy, Cast
AZ91C	M11914	Magnesium Alloy, Cast
AZ92A	M11920	Magnesium Alloy, Cast
B295.0	A22950	Aluminum Alloy, Cast–Permanent Mold Cast
B443.0	A24430	Aluminum Alloy, Cast–Sand and Permanent Mold Cast
B514.0	A25140	Aluminum Alloy, Cast–Sand Cast
B850.0	A28500	Aluminum Alloy, Cast–Sand and Permanent Mold Cast
B-1900		High Temperature Alloy–Nickel Base, Cast
Babbit (High Arsenic)		Lead Alloy, Cast–Lead Babbit Alloy

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
Barium Titanate		Flame (Thermal) Sprayed Material–Inorganic Coating Material
Berylco 41C		Beryllium Nickel Alloy, Wrought and Cast
Berylco 42C		Beryllium Nickel Alloy, Wrought and Cast
Berylco 43C		Beryllium Nickel Alloy, Wrought and Cast
Berylco 440		Beryllium Nickel Alloy, Wrought and Cast
Beryllia		Glasses & Ceramics–Ceramic
Beryllium Oxide		Glasses & Ceramics–Ceramic
Boron		Flame (Thermal) Sprayed Material–Inorganic Coating Material
Boron Epoxy		Composite
Bronze		Flame (Thermal) Sprayed Material–Sprayed Metals (Group II)
Brush Alloy 200C		Beryllium Nickel Alloy, Wrought and Cast
Brush Alloy 220C		Beryllium Nickel Alloy, Wrought and Cast
Brush Alloy 260C		Beryllium Nickel Alloy, Wrought and Cast
Brush Grade Carbon		Carbons & Graphites
C103		Refractory Alloy, Wrought, Cast, P/M–Columbium
C129Y		Refractory Alloy, Wrought, Cast, P/M–Columbium
C355.0	A33500	Aluminum Alloy, Cast–Sand and Permanent Mold Cast
C443.0	A04430	Aluminum Alloy, Cast–Die Casting
Calcium Titanate		Flame (Thermal) Sprayed Material–Inorganic Coating Material
Calcium Zirconate		Flame (Thermal) Sprayed Material–Inorganic Coating Material
Carbon Steel		Flame (Thermal) Sprayed Material–Sprayed Metals (Group III)
Cb-1Zr		Refractory Alloy, Wrought, Cast, P/M–Columbium
Cb-752		Refractory Alloy, Wrought, Cast, P/M–Columbium
Cellulose Acetate		Plastic–Thermoplastic
Chlorotrifluoroethylene		Plastic–Thermoplastic–Fluorocarbon
Chromium		Flame (Thermal) Sprayed Material–Sprayed Metals (Group II)
Chromium Carbide		Flame (Thermal) Sprayed Material–Sprayed Carbide
Chromium Carbide-Cobalt Blend		Flame (Thermal) Sprayed Material–Sprayed Carbide
Chromium Disilicide		Flame (Thermal) Sprayed Material–Inorganic Coating Material
Chromium Oxide		Flame (Thermal) Sprayed Material–Inorganic Coating Material
Chromium Plate		Plated Material
Co-Cr-B		Flame (Thermal) Sprayed Material–Corrosion and Oxidation Resistant Coating
Co-Cr-B Alloy (Self Fluxing)		Flame (Thermal) Sprayed Material–Sprayed Metals (Group I)
Cobalt		Flame (Thermal) Sprayed Material–Sprayed Metals (Group II)
Cobalt (40%), Zirconia Blend		Flame (Thermal) Sprayed Material–Inorganic Coating Material
Columax-5		Magnetic Alloy, Cast
Columbium		Flame (Thermal) Sprayed Material–Inorganic Coating Material
Columbium Carbide		Flame (Thermal) Sprayed Material–Sprayed Carbide
Copper	C38600	Powder Metal Alloy
Copper Alloys		Flame (Thermal) Sprayed Material
CT-0010-N		Powder Metal Alloy–Bronze
CT-0010-R		Powder Metal Alloy–Bronze
CT-0010-S		Powder Metal Alloy–Bronze
CTFE		Plastic–Thermoplastic–Fluorocarbon
Custom 450	S45000	Precipitation Hardening Stainless Steel, Wrought
Custom 455	S45500	Precipitation Hardening Stainless Steel, Wrought
CZN-1818-T		Powder Metal Alloy–Copper-Nickel Alloy
CZN-1818-U		Powder Metal Alloy–Copper-Nickel Alloy

26.2 Alphabetical List of Materials

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
CZN-1818-W		Powder Metal Alloy—Copper-Nickel Alloy
CZNP-1618-U		Powder Metal Alloy—Copper-Nickel Alloy
CZNP-1618-W		Powder Metal Alloy—Copper-Nickel Alloy
CZP-0218-T		Powder Metal Alloy—Brass
CZP-0218-U		Powder Metal Alloy—Brass
CZP-0218-W		Powder Metal Alloy—Brass
D2	T30402	Tool Steel, Wrought—Cold Work
D3	T30403	Tool Steel, Wrought—Cold Work
D4	T30404	Tool Steel, Wrought—Cold Work
D5	T30405	Tool Steel, Wrought—Cold Work
D6ac		High Strength Steel, Wrought
D7	T30407	Tool Steel, Wrought—Cold Work
D712.0	A47120	Aluminum Alloy, Cast—Sand Cast
DAP		Plastic—Thermosetting Plastic
Diallyl Phthalate		Plastic—Thermosetting Plastic
Discaloy	K66220	High Temperature Alloy—Iron Base, Wrought
DURANICKEL Alloy 301	N03301	Nickel Alloy, Wrought
Duriclor		High Silicon Cast Iron
Duriron		High Silicon Cast Iron
EC		Aluminum Alloy, Wrought
EZ33A	M12330	Magnesium Alloy, Cast
Epoxy		Plastic—Thermosetting Plastic
F-0000-N		Powder Metal Alloy—Iron
F-0000-P		Powder Metal Alloy—Iron
F-0000-R		Powder Metal Alloy—Iron
F-0000-S		Powder Metal Alloy—Iron
F-0000-T		Powder Metal Alloy—Iron
F-0005-S		Powder Metal Alloy—Steel
F-0008-P		Powder Metal Alloy—Steel
F-0008-S		Powder Metal Alloy—Steel
F1	T60601	Tool Steel, Wrought—Special Purpose
F2	T60602	Tool Steel, Wrought—Special Purpose
F332.0	A63320	Aluminum Alloy, Cast—Permanent Mold Cast
FC-0205-S		Powder Metal Alloy—Steel
FC-0208-P		Powder Metal Alloy—Steel
FC-0208-S		Powder Metal Alloy—Steel
FC-0508-P		Powder Metal Alloy—Steel
FC-1000-N		Powder Metal Alloy—Steel
Ferro-Tic		Machinable Carbide
Fiberglass Epoxy		Composite
FN-0205-S		Powder Metal Alloy—Steel
FN-0205-T		Powder Metal Alloy—Steel
FN-0405-R		Powder Metal Alloy—Steel
FN-0405-S		Powder Metal Alloy—Steel
FN-0405-T		Powder Metal Alloy—Steel
FS-85		Refractory Alloy, Wrought, Cast, P/M—Columbium

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
FS-291		Refractory Alloy, Wrought, Cast, P/M—Columbium
FSX-414		High Temperature Alloy—Cobalt Base, Cast
Furan		Plastic—Thermosetting Plastic
FX-1005-T		Powder Metal Alloy—Steel
FX-2008-T		Powder Metal Alloy—Steel
GE-218		Refractory Alloy, Wrought, Cast, P/M—Tungsten Alloy
Glass		Glasses & Ceramics
Glass (Kovar sealing)		Flame (Thermal) Sprayed Material—Inorganic Coating Material
GMR-235		High Temperature Alloy—Nickel Base, Cast
GMR-235D		High Temperature Alloy—Nickel Base, Cast
Gold	P00010	Precious Metal
Graphite		Carbons & Graphites
Graphite Epoxy		Composite
Greek Ascoloy	S41800	Stainless Steel, Wrought—Martensitic
Gyromet		Refractory Alloy, Wrought, Cast, P/M—Tungsten Alloy
H10	T20810	Tool Steel, Wrought—Hot Work
H11		High Strength Steel, Wrought
H11	T20811	Tool Steel, Wrought—Hot Work
H12	T20812	Tool Steel, Wrought—Hot Work
H13		High Strength Steel, Wrought
H13	T20813	Tool Steel, Wrought—Hot Work
H14	T20814	Tool Steel, Wrought—Hot Work
H19	T20819	Tool Steel, Wrought—Hot Work
H21	T20821	Tool Steel, Wrought—Hot Work
H22	T20822	Tool Steel, Wrought—Hot Work
H23	T20823	Tool Steel, Wrought—Hot Work
H24	T20824	Tool Steel, Wrought—Hot Work
H25	T20825	Tool Steel, Wrought—Hot Work
H26	T20826	Tool Steel, Wrought—Hot Work
H42	T20842	Tool Steel, Wrought—Hot Work
Hastelloy Alloy B	N10001	High Temperature Alloy—Nickel Base, Wrought or Cast
Hastelloy Alloy B-2	N10665	High Temperature Alloy—Nickel Base, Wrought
Hastelloy Alloy C	N10002	High Temperature Alloy—Nickel Base, Wrought or Cast
Hastelloy Alloy C-276	N10276	High Temperature Alloy—Nickel Base, Wrought
Hastelloy Alloy D		High Temperature Alloy—Nickel Base, Cast
Hastelloy Alloy G	N06007	High Temperature Alloy—Nickel Base, Wrought
Hastelloy Alloy S		High Temperature Alloy—Nickel Base, Wrought
Hastelloy Alloy X	N06002	High Temperature Alloy—Nickel Base, Wrought
Haynes Alloy 25	R30605	High Temperature Alloy—Cobalt Base, Wrought
Haynes Alloy 188	R30188	High Temperature Alloy—Cobalt Base, Wrought
Haynes Alloy 263	N07263	High Temperature Alloy—Nickel Base, Wrought
Hexaboron Silicide		Flame (Thermal) Sprayed Material—Inorganic Coating Material
Hi Perm 49		Magnetic Alloy
Hi Perm 49-FM		Free Machining Magnetic Alloy
Hiduminium RR-350		Aluminum Alloy, Cast—Sand Cast
HK31A	M13310	Magnesium Alloy, Cast
HK31A	M13310	Magnesium Alloy, Wrought
HM21A	M13210	Magnesium Alloy, Wrought

26.2 Alphabetical List of Materials

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
HM31A	M13312	Magnesium Alloy, Wrought
HNM		Precipitation Hardening Stainless Steel, Wrought
HOWMET #3		High Temperature Alloy—Cobalt Base, Cast
HP9-4-20		High Strength Steel, Wrought
HP9-4-25		High Strength Steel, Wrought
HP9-4-30		High Strength Steel, Wrought
HP9-4-45		High Strength Steel, Wrought
HS-6	R30006	High Temperature Alloy—Cobalt Base, Cast
HS-21	R30021	High Temperature Alloy—Cobalt Base, Cast
HS-31	R30031	High Temperature Alloy—Cobalt Base, Cast
HY80	J42015	Armor Plate, Ship Plate, Aircraft Plate, Wrought
HY100	J42240	Armor Plate, Ship Plate, Aircraft Plate, Wrought
HY180		Armor Plate, Ship Plate, Aircraft Plate, Wrought
HY230		Maraging Steel, Wrought
HyMu 80		Magnetic Alloy
Hyflux Alnico V-7		Magnetic Alloy, Cast
ILZRO 12		Zinc Alloy Cast
IN-100	N13100	High Temperature Alloy—Nickel Base, Cast
IN-102	N06102	High Temperature Alloy—Nickel Base, Wrought
IN-738		High Temperature Alloy—Nickel Base, Cast
IN-792		High Temperature Alloy—Nickel Base, Cast
Incolcy Alloy 800	N08800	High Temperature Alloy—Iron Base, Wrought
Incoloy Alloy 800H	N08810	High Temperature Alloy—Iron Base, Wrought
Incoloy Alloy 801	N08801	High Temperature Alloy—Iron Base, Wrought
Incoloy Alloy 802	N08802	High Temperature Alloy—Iron Base, Wrought
Incoloy Alloy 804	N06804	High Temperature Alloy—Nickel Base, Wrought
Incoloy Alloy 825	N08825	High Temperature Alloy—Nickel Base, Wrought
Incoloy Alloy 901	N09901	High Temperature Alloy—Nickel Base, Wrought
Incoloy Alloy 903	N19903	High Temperature Alloy—Nickel Base, Wrought
Inconel Alloy 600	N06600	High Temperature Alloy—Nickel Base, Wrought
Inconel Alloy 601	N06601	High Temperature Alloy—Nickel Base, Wrought
Inconel Alloy 617	N06617	High Temperature Alloy—Nickel Base, Wrought
Inconel Alloy 625	N06625	High Temperature Alloy—Nickel Base, Wrought
Inconel Alloy 700		High Temperature Alloy—Nickel Base, Wrought
Inconel Alloy 702	N07702	High Temperature Alloy—Nickel Base, Wrought
Inconel Alloy 706	N09706	High Temperature Alloy—Nickel Base, Wrought
Inconel Alloy 713C	N07713	High Temperature Alloy—Nickel Base, Cast
Inconel Alloy 718	N07718	High Temperature Alloy—Nickel Base, Wrought
Inconel Alloy 718	N07718	High Temperature Alloy—Nickel Base, Cast
Inconel Alloy 721	N07721	High Temperature Alloy—Nickel Base, Wrought
Inconel Alloy 722	N07722	High Temperature Alloy—Nickel Base, Wrought
Inconel Alloy X-750	N07750	High Temperature Alloy—Nickel Base, Wrought
Inconel Alloy 751	N07751	High Temperature Alloy—Nickel Base, Wrought
Invar	K93600	Controlled Expansion Alloy
Invar 36	K93602	Free Machining Controlled Expansion Alloy
Iron		Flame (Thermal) Sprayed Material
Iron		Flame (Thermal) Sprayed Material—Sprayed Metals (Group III)
J-1570		High Temperature Alloy—Cobalt Base, Wrought

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
K1A	M18010	Magnesium Alloy, Cast
Kevlar 49		Composite
Kovar	K94610	Controlled Expansion Alloy
L2	T61202	Tool Steel, Wrought—Special Purpose
L6	T61206	Tool Steel, Wrought—Special Purpose
L7	T61207	Tool Steel, Wrought—Special Purpose
L605	R30605	High Temperature Alloy—Cobalt Base, Wrought
Lead		Flame (Thermal) Sprayed Material
M1	T11301	Tool Steel, Wrought—High Speed
M2	T11302	Tool Steel, Wrought—High Speed
M3 Class 1	T11312	Tool Steel, Wrought—High Speed
M3 Class 2	T11323	Tool Steel, Wrought—High Speed
M4	T11304	Tool Steel, Wrought—High Speed
M6	T11306	Tool Steel, Wrought—High Speed
M7	T11307	Tool Steel, Wrought—High Speed
M10	T11310	Tool Steel, Wrought—High Speed
M30	T11330	Tool Steel, Wrought—High Speed
M33	T11333	Tool Steel, Wrought—High Speed
M34	T11334	Tool Steel, Wrought—High Speed
M36	T11336	Tool Steel, Wrought—High Speed
M41	T11341	Tool Steel, Wrought—High Speed
M42	T11342	Tool Steel, Wrought—High Speed
M43	T11343	Tool Steel, Wrought—High Speed
M44	T11344	Tool Steel, Wrought—High Speed
M46	T11346	Tool Steel, Wrought—High Speed
M47	T11347	Tool Steel, Wrought—High Speed
M-50	T11350	Alloy Steel, Wrought—High Carbon
M252	N07252	High Temperature Alloy—Nickel Base, Wrought
MACOR		Glasses & Ceramics—Machinable Glass-Ceramic
Magnesia		ses & Ceramics—Ceramic
Magnesia Alumina Spinel		e (Thermal) Sprayed Material—Inorganic Coating Material
Magnesium Oxide		Gla. es & Ceramics—Ceramic
Magnesium Zirconate		Flame (Thermal) Sprayed Material—Inorganic Coating Material
Magnetic Core Iron-FM (up to 2.5% Si)		Free Machining Magnetic Alloy
Magnetic Core Iron (up to 4% Si)		Magnetic Alloy
Mallory 2000		Refractory Alloy, Wrought, Cast, P/M—Tungsten Alloy
Manganese		Manganese, Wrought
MAR-M200		High Temperature Alloy—Nickel Base, Cast
MAR-M246		High Temperature Alloy—Nickel Base, Cast
MAR-M302		High Temperature Alloy—Cobalt Base, Cast
MAR-M322		High T mperature Alloy—Cobalt Base, Cast
MAR-M421		High Temperature Alloy—Nickel Base, Cast
MAR-M432		High Temperature Alloy—Nickel Base, Cast
MAR-M509		High Temperature Alloy—Cobalt Base, Cast
MAR-M905		High Temperature Alloy—Cobalt Base, Wrought
MAR-M918		High Temperature Alloy—Cobalt Base, Wrought

26.2 Alphabetical List of Materials

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
Mechanical Grades		Carbons & Graphites
Melamine		Plastic–Thermosetting Plastic
Mica		Glasses & Ceramics–Mineral Silicate
MIL-S-12560		Armor Plate. Ship Plate. Aircraft Plate. Wrought
MIL-S-16216	J42015	Armor Plate. Ship Plate. Aircraft Plate. Wrought
MIL-S-16216	J42240	Armor Plate. Ship Plate. Aircraft Plate. Wrought
Mo		Refractory Alloy. Wrought. Cast. P/M–Molybdenum
Mo-50Re		Refractory Alloy. Wrought. Cast. P/M–Molybdenum
Molybdenum		Flame (Thermal) Sprayed Material–Sprayed Metals (Group II)
Molybdenum Disilicide		Flame (Thermal) Sprayed Material–Inorganic Coating Material
Monel		Flame (Thermal) Sprayed Material–Sprayed Metals (Group II)
MONEL Alloy 400	N04400	Nickel Alloy. Wrought
MONEL Alloy 401	N04401	Nickel Alloy. Wrought
MONEL Alloy 404	N04404	Nickel Alloy. Wrought
MONEL Alloy 502	N05502	Nickel Alloy. Wrought
MONEL Alloy K500	N05500	Nickel Alloy. Wrought
MONEL Alloy R405	N04405	Nickel Alloy. Wrought
Mullite		Flame (Thermal) Sprayed Material–Inorganic Coating Material
Mullite		Glasses & Ceramics–Ceramic
N-155	R30155	High Temperature Alloy–Iron Base. Wrought
NASA Co-W-Re		High Temperature Alloy–Cobalt Base. Cast
Ni-Cr-B		Flame (Thermal) Sprayed Material–Corrosion and Oxidation Resistant Coating
Ni-Cr-B Alloys (Self Fluxing)		Flame (Thermal) Sprayed Material–Sprayed Metals (Group I)
Nickel		Flame (Thermal) Sprayed Material–Sprayed Metals (Group II)
Nickel		Powder Metal Alloy–Nickel and Nickel Alloy
Nickel 200	N02200	Nickel Alloy. Wrought and Cast
Nickel 201	N02201	Nickel Alloy. Wrought
Nickel 205	N02205	Nickel Alloy. Wrought
Nickel 211	N02211	Nickel Alloy. Wrought
Nickel 220	N02220	Nickel Alloy. Wrought
Nickel 230	N02230	Nickel Alloy. Wrought
Nickel (40%). Alumina Blend		Flame (Thermal) Sprayed Material–Inorganic Coating Material
Nickel Alloys		Flame (Thermal) Sprayed Material
Nickel Chrome Steel (Special)		Flame (Thermal) Sprayed Material–Sprayed Metals (Group I)
Nickel Oxide		Flame (Thermal) Sprayed Material–Inorganic Coating Material
Nickel Plate		Plated Material
Nimonic 75	N05075	High Temperature Alloy–Nickel Base. Wrought
Nimonic 80	N07080	High Temperature Alloy–Nickel Base. Wrought
Nimonic 90	N07090	High Temperature Alloy–Nickel Base. Wrought
Nimonic 95		High Temperature Alloy–Nickel Base. Wrought
Niobium Alloy		Flame (Thermal) Sprayed Material–Inorganic Coating Material
NI-SPAN-C 902	N09902	Nickel Alloy. Wrought
Nitinol 55Ni-45Ti		Nitinol Alloy. Wrought
Nitinol 56Ni-44Ti		Nitinol Alloy. Wrought
Nitinol 60Ni-40Ti		Nitinol Alloy. Wrought
Nitralloy 125		Nitriding Steel. Wrought
Nitralloy 135		Nitriding Steel. Wrought
Nitralloy 135 Mod.		Nitriding Steel. Wrought

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
Nitralloy 225		Nitriding Steel, Wrought
Nitralloy 230		Nitriding Steel, Wrought
Nitralloy EZ		Nitriding Steel, Wrought
Nitralloy N		Nitriding Steel, Wrought
Nitrex 1		Nitriding Steel, Wrought
Nitronic 32	S24100	Stainless Steel, Wrought—Austenitic
Nitronic 33	S24000	Stainless Steel, Wrought—Austenitic
Nitronic 40	S21900	Stainless Steel, Wrought—Austenitic
Nitronic 50	S20910	Stainless Steel, Wrought—Austenitic
Nitronic 60	S21800	Stainless Steel, Wrought—Austenitic
Nylons, Unfilled		Plastics—Thermoplastics
Nylons, 35% Glass reinforced		Plastics—Thermoplastics
O1	T31501	Tool Steel, Wrought—Cold Work
O2	T31502	Tool Steel, Wrought—Cold Work
O6	T31506	Tool Steel, Wrought—Cold Work
O7	T31507	Tool Steel, Wrought—Cold Work
P2	T51602	Tool Steel, Wrought—Mold
P4	T51604	Tool Steel, Wrought—Mold
P5	T51605	Tool Steel, Wrought—Mold
P6	T51606	Tool Steel, Wrought—Mold
P20	T51620	Tool Steel, Wrought—Mold
P21	T51621	Tool Steel, Wrought—Mold
PERMANICKEL Alloy 300	N03300	Nickel Alloy, Wrought
PH 13-8Mo	S13800	Precipitation Hardening Stainless Steel, Wrought
PH 14-8Mo	S14800	Precipitation Hardening Stainless Steel, Wrought
PH 15-7Mo	S15700	Precipitation Hardening Stainless Steel, Wrought
Phenolic		Plastic—Thermosetting Plastic
Platinum		Flame (Thermal) Sprayed Material
Platinum	P04995	Precious Metal
Polyamides—Unfilled		Plastic—Thermoplastic
Polyamides—35% Glass reinforced		Plastic—Thermoplastic
Polyimide		Plastic—Thermosetting Plastic
Polyimide—Glass filled		Plastic—Thermosetting Plastic
Polyarylether		Plastic—Thermoplastic
Polybutadiene		Plastic—Thermosetting Plastic
Polycarbonate		Plastic—Thermoplastic
Polyethylene		Plastic—Thermoplastic
Polypropylene		Plastic—Thermoplastic
Polysulfone		Plastic—Thermoplastic
Polystyrene		Plastic—Thermoplastic
Polyurethane		Plastic—Thermosetting Plastic
Porcelain Enamel		Glasses & Ceramics—Ceramic
Precipitation Hardening Steel		Flame (Thermal) Sprayed Material—Sprayed Metals (Group III)
PYROCERAM		Glasses & Ceramics—Polycrystalline Glass

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MATERIAL	UNS DESIGNATION	MATERIAL GROUP
QE22A	M18220	Magnesium Alloy, Cast
Rare Earth Oxides		Flame (Thermal) Sprayed Material—Inorganic Coating Material
Refractaloy 26		High Temperature Alloy—Nickel Base, Wrought
Rene 41	N07041	High Temperature Alloy—Nickel Base, Wrought
Rene 63		High Temperature Alloy—Nickel Base, Wrought
Rene 77		High Temperature Alloy—Nickel Base, Wrought
Rene 80		High Temperature Alloy—Nickel Base, Cast
Rene 95		High Temperature Alloy—Nickel Base, Wrought
Rene 100	N13100	High Temperature Alloy—Nickel Base, Cast
Rene 125		High Temperature Alloy—Nickel Base, Cast
Rubber		Rubber
S1	T41901	Tool Steel, Wrought—Shock Resisting
S2	T41902	Tool Steel, Wrought—Shock Resisting
S5	T41905	Tool Steel, Wrought—Shock Resisting
S6	T41906	Tool Steel, Wrought—Shock Resisting
S7	T41907	Tool Steel, Wrought—Shock Resisting
S-816	R30816	High Temperature Alloy—Cobalt Base, Wrought
SAE J158:		
Grade M3210	F20000	Malleable Cast Iron—Ferritic
Grade M4504	F20001	Malleable Cast Iron—Pearlitic
Grade M5003	F20002	Malleable Cast Iron—Pearlitic
Grade M5503	F20003	Malleable Cast Iron—Tempered Martensite
Grade M7002	F20004	Malleable Cast Iron—Tempered Martensite
Grade M8501	F20005	Malleable Cast Iron—Tempered Martensite
SAE J431c:		
Grade G1800	F10004	Gray Cast Iron—Ferritic
Grade G2500	F10005	Gray Cast Iron—Pearlitic-Ferritic
Grade G3000	F10006	Gray Cast Iron—Pearlitic
Grade G3500	F10007	Gray Cast Iron—Pearlitic + Free Carbides
Grade G4000	F10008	Gray Cast Iron—Pearlitic + Free Carbides
SAE J434c:		
Grade D4018	F32800	Ductile Cast Iron—Ferritic
Grade D4512	F33100	Ductile Cast Iron—Ferritic
Grade D5506	F33800	Ductile Cast Iron—Ferritic-Pearlitic
Grade D7003	F34800	Ductile Cast Iron—Pearlitic-Martensitic
Grade DQ&T	F30000	Ductile Cast Iron—Martensitic
SAE J438b:		
Type W108	T72301	Tool Steel, Wrought—Water Hardening
Type W109	T72301	Tool Steel, Wrought—Water Hardening
Type W110	T72301	Tool Steel, Wrought—Water Hardening
Type W112	T72301	Tool Steel, Wrought—Water Hardening
Type W209	T72302	Tool Steel, Wrought—Water Hardening
Type W210	T72302	Tool Steel, Wrought—Water Hardening
Type W310	T72303	Tool Steel, Wrought—Water Hardening
SAE J469a:		
Grade 903 (AG40A)	Z33520	Zinc Alloy, Cast
Grade 925 (AC41A)	Z35531	Zinc Alloy, Cast
SEL		High Temperature Alloy—Nickel Base, Cast

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
SEL 15		High Temperature Alloy–Nickel Base, Cast
Silicon Carbide		Glasses & Ceramics–Ceramic
Silicon Nitride		Glasses & Ceramics–Ceramic
Silicone		Plastic–Thermosetting Plastic
Silicone-Glass filled		Plastic–Thermosetting Plastic
Silver		Flame (Thermal) Sprayed Material
Silver	P07010	Precious Metal
Silver Plate		Plated Material
SS-303-R		Powder Metal Alloy–Stainless Steel
SS-304-R		Powder Metal Alloy–Stainless Steel
SS-316-R		Powder Metal Alloy–Stainless Steel
SS-410-R		Powder Metal Alloy–Stainless Steel
Stainless Steels		Flame (Thermal) Sprayed Material–Sprayed Metals (Group I)
Stainless Steels–Austenitic		Flame (Thermal) Sprayed Material
Stainless Steels–Ferritic		Flame (Thermal) Sprayed Material
Stainless W	S17600	Precipitation Hardening Stainless Steel, Wrought
Steels		Flame (Thermal) Sprayed Material
Structural Steels		See Numerical Listing According to Tensile Yield Strength
T1	T12001	Tool Steel, Wrought–High Speed
T2	T12002	Tool Steel, Wrought–High Speed
T4	T12004	Tool Steel, Wrought–High Speed
T5	T12005	Tool Steel, Wrought–High Speed
T6	T12006	Tool Steel, Wrought–High Speed
T8	T12008	Tool Steel, Wrought–High Speed
T15	T12015	Tool Steel, Wrought–High Speed
T-111		Refractory Alloy, Wrought, Cast, P/M–Tantalum
T-222		Refractory Alloy, Wrought, Cast, P/M–Tantalum
Ta-10W		Refractory Alloy, Wrought, Cast, P/M–Tantalum
Ta63		Refractory Alloy, Wrought, Cast, P/M–Tantalum
Ta-Hf		Refractory Alloy, Wrought, Cast, P/M–Tantalum
Tantalum		Flame (Thermal) Sprayed Material–Inorganic Coating Material
Tantalum Carbide		Flame (Thermal) Sprayed Material–Sprayed Carbide
TD-Nickel		High Temperature Alloy–Nickel Base, Wrought
TD-Ni-Cr		High Temperature Alloy–Nickel Base, Wrought
Tetrafluoroethylene		Plastic–Thermoplastic–Fluorocarbon
TFE		Plastic–Thermoplastic–Fluorocarbon
Thermoplastics		Plastics
Thermosetting Plastics		Plastics
Thoria		Glasses & Ceramics–Ceramic
Thorium Oxide		Glasses & Ceramics–Ceramic
TiCODE-12		Titanium Alloy, Wrought–Commercially Pure
Ti-0.2Pd	R52400	Titanium Alloy, Wrought or Cast–Commercially Pure
Ti-17		Titanium Alloy, Wrought–Alpha-Beta Alloy
Ti 98.9		Titanium Alloy, Wrought–Commercially Pure
Ti 99.0		Titanium Alloy, Wrought or Cast–Commercially Pure
Ti 99.2		Titanium Alloy, Wrought–Commercially Pure
Ti 99.5		Titanium Alloy, Wrought–Commercially Pure
Ti-1Al-8V-5Fe		Titanium Alloy, Wrought–Alpha and Alpha-Beta Alloy
Ti-2Al-11Sn-5Zr-1Mo	R54790	Titanium Alloy, Wrought–Alpha and Alpha-Beta Alloy
Ti-3Al-2.5V	R56320	Titanium Alloy, Wrought–Alpha-Beta Alloy

26.2 Alphabetical List of Materials

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
Ti-3Al-8V-6Cr-4Mo-4Zr	R58640	Titanium Alloy, Wrought—Beta Alloy
Ti-4.5Sn-6Zr-11.5Mo	R58030	Titanium Alloy, Wrought—Beta Alloy
Ti-5Al-2Sn-2Zr-4Mo-4Cr		Titanium Alloy, Wrought—Alpha-Beta Alloy
Ti-5Al-2.5Sn	R54521	Titanium Alloy, Wrought or Cast—Alpha Alloy
Ti-5Al-2.5Sn ELI	R54520	Titanium Alloy, Wrought—Alpha Alloy
Ti-5Al-6Sn-2Zr-1Mo	R54560	Titanium Alloy, Wrought—Alpha and Alpha-Beta Alloy
Ti-6Al-2Cb-1Ta-0.8Mo	R56210	Titanium Alloy, Wrought—Alpha-Beta Alloy
Ti-6Al-2Sn-4Zr-2Mo	R54620	Titanium Alloy, Wrought or Cast—Alpha-Beta Alloy
Ti-6Al-2Sn-4Zr-2Mo-.25Si		Titanium Alloy, Wrought—Alpha-Beta Alloy
Ti-6Al-2Sn-4Zr-6Mo	R56260	Titanium Alloy, Wrought—Alpha-Beta Alloy
Ti-6Al-4V	R56401	Titanium Alloy, Wrought or Cast—Alpha-Beta Alloy
Ti-6Al-4V ELI	R56400	Titanium Alloy, Wrought—Alpha-Beta Alloy
Ti-6Al-6V-2Sn	R56620	Titanium Alloy, Wrought—Alpha-Beta Alloy
Ti-7Al-4Mo	R56740	Titanium Alloy, Wrought—Alpha-Beta Alloy
Ti-8Al-1Mo-1V	R54810	Titanium Alloy, Wrought or Cast—Alpha and Alpha-Beta Alloy
Ti-8Mn	R56080	Titanium Alloy, Wrought—Alpha-Beta Alloy
Ti-8Mo-8V-2Fe-3Al	R58820	Titanium Alloy, Wrought—Beta Alloy
Ti-10V-2Fe-3Al		Titanium Alloy, Wrought—Beta Alloy
Ti-13V-11Cr-3Al	R58010	Titanium Alloy, Wrought—Beta Alloy
Tin		Flame (Thermal) Sprayed Material
Titania		Glasses & Ceramics—Ceramic
Titania (50%), Alumina Blend		Flame (Thermal) Sprayed Material—Inorganic Coating Material
Titanium Carbide		Carbide
Titanium Carbide		Flame (Thermal) Sprayed Material—Sprayed Carbide
Titanium Diboride		Glasses & Ceramics—Ceramic
Titanium Oxide		Flame (Thermal) Sprayed Material—Inorganic Coating Material
Titanium Oxide		Glasses & Ceramics—Ceramic
TRW VI A		High Temperature Alloy—Nickel Base, Cast
Tungsten		Flame (Thermal) Sprayed Material—Inorganic Coating Material
Tungsten, 85% Density		Refractory Alloy, Wrought, Cast, P/M—Tungsten
Tungsten, 93% Density		Refractory Alloy, Wrought, Cast, P/M—Tungsten
Tungsten, 96% Density		Refractory Alloy, Wrought, Cast, P/M—Tungsten
Tungsten, 100% Density		Refractory Alloy, Wrought, Cast, P/M—Tungsten
Tungsten-2 Thoria		Refractory Alloy, Wrought, Cast, P/M—Tungsten
Tungsten Carbide		Carbide
Tungsten Carbide		Flame (Thermal) Sprayed Material—Sprayed Carbide
Tungsten Carbide-Cobalt		Flame (Thermal) Sprayed Material—Sprayed Carbide
Tungsten Carbide (Cobalt)-Nickel Alloy Blend		Flame (Thermal) Sprayed Material—Sprayed Carbide
TZC		Refractory Alloy, Wrought, Cast, P/M—Molybdenum
TZM		Refractory Alloy, Wrought, Cast, P/M—Molybdenum
Udimet 500	N07500	High Temperature Alloy—Nickel Base, Wrought or Cast
Udimet 630		High Temperature Alloy—Nickel Base, Wrought
Udimet 700		High Temperature Alloy—Nickel Base, Wrought or Cast
Udimet 710		High Temperature Alloy—Nickel Base, Wrought
Unitemp 1753		High Temperature Alloy—Nickel Base, Wrought
Uranium	M08990	Uranium, Wrought

MATERIAL	UNS DESIGNATION	MATERIAL GROUP
V-36		High Temperature Alloy–Cobalt Base. Wrought
V-57		High Temperature Alloy–Iron Base. Wrought
W1	T72301	Tool Steel. Wrought–Water Hardening
W2	T72302	Tool Steel. Wrought–Water Hardening
W5	T72305	Tool Steel. Wrought–Water Hardening
W-5Re		Refractory Alloy. Wrought. Cast. P/M–Tungsten Alloy
W-7Ni-4Cu		Refractory Alloy. Wrought. Cast. P/M–Tungsten Alloy
W-10Ag		Refractory Alloy. Wrought. Cast. P/M–Tungsten Alloy
W-15Mo		Refractory Alloy. Wrought. Cast. P/M–Tungsten Alloy
W-25Re		Refractory Alloy. Wrought. Cast. P/M–Tungsten Alloy
W-25Re-30Mo		Refractory Alloy. Wrought. Cast. P/M–Tungsten Alloy
W-545	K66545	High Temperature Alloy–Iron Base. Wrought
Waspaloy	N07001	High Temperature Alloy–Nickel Base. Wrought
WC-3015		Refractory Alloy. Wrought. Cast. P/M–Columbium
WI-52		High Temperature Alloy–Cobalt Base. Cast
X-40	R30031	High Temperature Alloy–Cobalt Base. Cast
X-45		High Temperature Alloy–Cobalt Base. Cast
Yttrium Zirconate		Flame (Thermal) Sprayed Material–Inorganic Coating Material
ZDC No. 7	Z33520	Zinc Alloy. Cast
ZE41A	M16410	Magnesium Alloy. Cast
ZE63A	M16630	Magnesium Alloy. Cast
ZH62A	M16620	Magnesium Alloy. Cast
Zinc		Flame (Thermal) Sprayed Material
Zircaloy 2 (Grade 32)	R60802	Zirconium Alloy. Wrought
Zircaloy 4 (Grade 34)	R60804	Zirconium Alloy. Wrought
Zircon		Glasses & Ceramics–Ceramic
Zirconia		Glasses & Ceramics–Ceramic
Zirconia (Lime Stabilized)		Flame (Thermal) Sprayed Material–Inorganic Coating Material
Zirconia. Nickel-Aluminide Blends		Flame (Thermal) Sprayed Material–Inorganic Coating Material
Zirconium Oxide		Glasses & Ceramics–Ceramic
Zirconium Oxide (Hafnia Free. Lime Stabilized)		Flame (Thermal) Sprayed Material–Inorganic Coating Material
Zirconium Silicate		Flame (Thermal) Sprayed Material–Inorganic Coating Material
Zirconium Silicate		Glasses & Ceramics–Ceramic
ZK40A	M16400	Magnesium Alloy. Wrought
ZK51A	M16510	Magnesium Alloy. Cast
ZK60A	M16600	Magnesium Alloy. Wrought
ZK61A	M16610	Magnesium Alloy. Cast
Zr-0.001%Hf (Grade 21)		Zirconium Alloy. Wrought
Zr-2%Hf (Grade 11)		Zirconium Alloy. Wrought

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CHEMICAL COMPOSITION

The following tables contain approximate chemical compositions for materials included in this edition of the *Machining Data Handbook*. Chemistries are presented in the same material groupings as are specified in the machining recommendations, sections 1 through 8.

These tables are designed to assist in locating machining recommendations for material designations not listed in the handbook, but for which a chemical composition is known. Scanning the tables, the known composition can be matched with an identical or similar material designation and handbook group. Once this has been accomplished, machining recommendations can be selected for the material using the material group and designation identified.

Please note that chemical compositions were not provided for the following material groups:

22. Compacted Graphite Cast Irons
44. Uranium, Wrought
46. Manganese, Wrought
48. Machinable Carbides
49. Carbides
54. Carbons & Graphites
55. Glasses & Ceramics
56. Plastics
57. Composites
58. Flame (Thermal) Sprayed Materials
59. Plated Materials
60. Precious Metals
61. Rubber

The chemical elements and their symbols are listed below.

Actinium	Ac	Germanium	Ge	Praseodymium	Pr
Aluminum	Al	Gold	Au	Promethium	Pm
Americium	Am	Hafnium	Hf	Protactinium	Pa
Antimony	Sb	Helium	He	Radium	Ra
Argon	A	Holmium	Ho	Radon	Rn
Arsenic	As	Hydrogen	H	Rhenium	Re
Astatine	At	Indium	In	Rhodium	Rh
Barium	Ba	Iodine	I	Rubidium	Rb
Berkelium	Bk	Iridium	Ir	Ruthenium	Ru
Beryllium	Se	Iron	Fe	Samarium	Sm
Bismuth	Bi	Krypton	Kr	Scandium	Sc
Boron	B	Lanthanum	La	Selenium	Se
Bromine	Br	Lead	Pb	Silicon	Si
Cadmium	Cd	Lithium	Li	Silver	Ag
Calcium	Ca	Lutetium	Lu	Sodium	Na
Californium	Cf	Magnesium	Mg	Strontium	Sr
Carbon	C	Manganese	Mn	Sulfur	S
Cerium	Ce	Mendelevium	Mv	Tantalum	Ta
Cesium	Cs	Mercury	Hg	Technetium	Tc
Chlorine	Cl	Molybdenum	Mo	Tellurium	Te
Chromium	Cr	Neodymium	Nd	Terbium	Tb
Cobalt	Co	Neon	Ne	Thallium	Tl
Columbium	Cb	Neptunium	Np	Thorium	Th
Copper	Cu	Nickel	Ni	Thulium	Tm
Curium	Cm	Nitrogen	N	Tin	Sn
Dysprosium	Dy	Nobelium	No	Titanium	Ti
Einsteinium	E	Osmium	Os	Tungsten	W
Erbium	Er	Oxygen	O	Uranium	U
Europium	Eu	Palladium	Pd	Vanadium	V
Fermium	Fm	Phosphorus	P	Xenon	Xe
Fluorine	F	Platinum	Pt	Ytterbium	Yb
Francium	Fr	Plutonium	Pu	Yttrium	Y
Gadolinium	Gd	Polonium	Po	Zinc	Zn
Gallium	Ga	Potassium	K	Zirconium	Zr

COMPOSITION, %																	
Fe	C	Ni	Cr	Mo	V	Mn	Si	P	S	Pb	Co	Ti	Al	—	—	Other	MATERIAL DESIGNATION
1. FREE MACHINING CARBON STEELS, WROUGHT — Low Carbon Resulfurized																	
bal	.08	—	—	—	—	.65	—	.04	.10	—	—	—	—				1108
bal	.09	—	—	—	—	.75	—	.04	.10	—	—	—	—				1109
bal	.10	—	—	—	—	.45	—	.04	.10	—	—	—	—				1110
bal	.11	—	—	—	—	.75	—	.10	.12	—	—	—	—				1211
bal	.12	—	—	—	—	.85	—	.10	.19	—	—	—	—				1212
bal	.13	—	—	—	—	.85	—	.10	.28	—	—	—	—				1213
bal	.15	—	—	—	—	.75	—	.04	.10	—	—	—	—				1115
bal	.15	—	—	—	—	.90	—	.06	.31	—	—	—	—				1215
bal	.16	—	—	—	—	1.30	—	.04	20	—	—	—	—				1116
bal	.17	—	—	—	—	1.20	—	.04	.10	—	—	—	—				1117
bal	.18	—	—	—	—	1.50	—	.04	.10	—	—	—	—				1118
bal	.19	—	—	—	—	1.20	—	.04	.30	—	—	—	—				1119
1. FREE MACHINING CARBON STEELS, WROUGHT — Medium Carbon Resulfurized																	
bal	.32	—	—	—	—	1.50	—	.04	.10	—	—	—	—				1132
bal	.37	—	—	—	—	1.50	—	.04	.10	—	—	—	—				1137
bal	.39	—	—	—	—	1.50	—	.04	.20	—	—	—	—				1139
bal	.40	—	—	—	—	.85	—	.04	.10	—	—	—	—				1140
bal	.41	—	—	—	—	1.50	—	.04	.10	—	—	—	—				1141
bal	.44	—	—	—	—	1.50	—	.04	.30	—	—	—	—				1144
bal	.45	—	—	—	—	.85	—	.04	.05	—	—	—	—				1145
bal	.46	—	—	—	—	.85	—	.04	.10	—	—	—	—				1146
bal	.51	—	—	—	—	.85	—	.04	.10	—	—	—	—				1151
1. FREE MACHINING CARBON STEELS, WROUGHT — Low Carbon Leaded																	
bal	.09	—	—	—	—	.90	—	.06	.30	.25	—	—	—				12L15
bal	.13	—	—	—	—	.85	—	.10	.29	.25	—	—	—				12L13
bal	.15	—	—	—	—	1.00	—	.07	.31	.25	—	—	—				12L14
bal	.17	—	—	—	—	1.20	—	.04	.10	.25	—	—	—				11L17
bal	.18	—	—	—	—	.75	—	.04	.05	.25	—	—	—				10L18

COMPOSITION, %																	
Fe	C	Ni	Cr	Mo	V	Mn	Si	P	S	Pb	Co	Ti	Al	—	—	Other	MATERIAL DESIGNATION
1. FREE MACHINING CARBON STEELS, WROUGHT — Medium Carbon Leaded																	
bal	.37	—	—	—	—	1.50	—	.04	.10	.25	—	—	—				11L37
bal	.41	—	—	—	—	1.50	—	.04	.10	.25	—	—	—				11L41
bal	.44	—	—	—	—	1.50	—	.04	.28	.25	—	—	—				11L44
bal	.45	—	—	—	—	.75	—	.04	.05	.25	—	—	—				10L45
bal	.50	—	—	—	—	.75	—	.04	.05	.25	—	—	—				10L50
2. CARBON STEELS, WROUGHT — Low Carbon																	
bal	.05	—	—	—	—	.30	—	.04	.05	—	—	—	—				1005
bal	.06	—	—	—	—	.35	—	.04	.05	—	—	—	—				1006
bal	.08	—	—	—	—	.40	—	.04	.05	—	—	—	—				1008
bal	.09	—	—	—	—	.60	—	.04	.05	—	—	—	—				1009
bal	.10	—	—	—	—	.45	—	.04	.05	—	—	—	—				1010
bal	.11	—	—	—	—	.75	—	.04	.05	—	—	—	—				1011
bal	.12	—	—	—	—	.45	—	.04	.05	—	—	—	—				1012
bal	.13	—	—	—	—	.65	—	.04	.05	—	—	—	—				1013
bal	.13	—	—	—	—	1.30	—	.04	.05	—	—	—	—				1513
bal	.15	—	—	—	—	.45	—	.04	.05	—	—	—	—				1015
bal	.16	—	—	—	—	.75	—	.04	.05	—	—	—	—				1016
bal	.17	—	—	—	—	.45	—	.04	.05	—	—	—	—				1017
bal	.18	—	—	—	—	.75	—	.04	.05	—	—	—	—				1018
bal	.18	—	—	—	—	1.30	—	.04	.05	—	—	—	—				1518
bal	.19	—	—	—	—	.85	—	.04	.05	—	—	—	—				1019
bal	.20	—	—	—	—	.45	—	.04	.05	—	—	—	—				1020
bal	.21	—	—	—	—	.75	—	.04	.05	—	—	—	—				1021
bal	.22	—	—	—	—	.85	—	.04	.05	—	—	—	—				1022
bal	.22	—	—	—	—	1.30	—	.04	.05	—	—	—	—				1522
bal	.23	—	—	—	—	.45	—	.04	.05	—	—	—	—				1023
bal	.25	—	—	—	—	.45	—	.04	.05	—	—	—	—				1025
bal	.26	—	—	—	—	.75	—	.04	.05	—	—	—	—				1026
bal	.29	—	—	—	—	.75	—	.04	.05	—	—	—	—				1029

COMPOSITION, %																	MATERIAL DESIGNATION
Fe	C	Ni	Cr	Mo	V	Mn	Si	P	S	Pb	Co	Ti	Al	—	—	Other	
2. CARBON STEELS, WROUGHT — Medium Carbon																	
bal	.24	—	—	—	—	1.50	—	.04	.05	—	—	—	—				1524
bal	.25	—	—	—	—	.95	—	.04	.05	—	—	—	—				1525
bal	.26	—	—	—	—	1.30	—	.04	.05	—	—	—	—				1526
bal	.27	—	—	—	—	1.40	—	.04	.05	—	—	—	—				1527
bal	.30	—	—	—	—	.75	—	.04	.05	—	—	—	—				1030
bal	.33	—	—	—	—	.85	—	.04	.05	—	—	—	—				1033
bal	.35	—	—	—	—	.75	—	.04	.05	—	—	—	—				1035
bal	.36	—	—	—	—	1.40	—	.04	.05	—	—	—	—				1536
bal	.37	—	—	—	—	.85	—	.04	.05	—	—	—	—				1037
bal	.38	—	—	—	—	.75	—	.04	.05	—	—	—	—				1033
bal	.39	—	—	—	—	.85	—	.04	.05	—	—	—	—				1039
bal	.40	—	—	—	—	.75	—	.04	.05	—	—	—	—				1040
bal	.41	—	—	—	—	1.50	—	.04	.05	—	—	—	—				1541
bal	.42	—	—	—	—	.75	—	.04	.05	—	—	—	—				1042
bal	.43	—	—	—	—	.85	—	.04	.05	—	—	—	—				1043
bal	.44	—	—	—	—	.45	—	.04	.05	—	—	—	—				1044
bal	.45	—	—	—	—	.75	—	.04	.05	—	—	—	—				1045
bal	.46	—	—	—	—	.85	—	.04	.05	—	—	—	—				1046
bal	.47	—	—	—	—	1.50	—	.04	.05	—	—	—	—				1547
bal	.48	—	—	—	—	1.30	—	.04	.05	—	—	—	—				1548
bal	.49	—	—	—	—	.75	—	.04	.05	—	—	—	—				1049
bal	.50	—	—	—	—	.75	—	.04	.05	—	—	—	—				1050
bal	.51	—	—	—	—	1.00	—	.04	.05	—	—	—	—				1551
bal	.52	—	—	—	—	1.40	—	.04	.05	—	—	—	—				1552
bal	.53	—	—	—	—	.85	—	.04	.05	—	—	—	—				1053
bal	.55	—	—	—	—	.75	—	.04	.05	—	—	—	—				1055

COMPOSITION, %																MATERIAL DESIGNATION
Fe	C	Ni	Cr	Mo	V	Mn	Si	P	S	Pb	Co	Ti	Al	—	—	Other
2. CARBON STEELS, WROUGHT — High Carbon																
bal	.60	—	—	—	—	.75	—	.04	.05	—	—	—	—			1060
bal	.61	—	—	—	—	.90	—	.04	.05	—	—	—	—			1561
bal	.64	—	—	—	—	.65	—	.04	.05	—	—	—	—			1064
bal	.65	—	—	—	—	.75	—	.04	.05	—	—	—	—			1065
bal	.66	—	—	—	—	1.00	—	.04	.05	—	—	—	—			1566
bal	.69	—	—	—	—	.55	—	.04	.05	—	—	—	—			1069
bal	.70	—	—	—	—	.75	—	.04	.05	—	—	—	—			1070
bal	.72	—	—	—	—	1.20	—	.04	.05	—	—	—	—			1572
bal	.74	—	—	—	—	.65	—	.04	.05	—	—	—	—			1074
bal	.75	—	—	—	—	.55	—	.04	.05	—	—	—	—			1075
bal	.78	—	—	—	—	.45	—	.04	.05	—	—	—	—			1078
bal	.80	—	—	—	—	.75	—	.04	.05	—	—	—	—			1080
bal	.84	—	—	—	—	.75	—	.04	.05	—	—	—	—			1084
bal	.85	—	—	—	—	.85	—	.04	.05	—	—	—	—			1085
bal	.86	—	—	—	—	.45	—	.04	.05	—	—	—	—			1086
bal	.90	—	—	—	—	.75	—	.04	.05	—	—	—	—			1090
bal	.95	—	—	—	—	.45	—	.04	.05	—	—	—	—			1095
3. CARBON AND FERRITIC ALLOY STEELS (HIGH TEMPERATURE SERVICE)																
bal	.20	—	—	—	—	.60	.20	.04	.05	—	—	—	—			ASTM A369 Grade FPA
bal	.25	—	—	—	—	.65	.20	.04	.05	—	—	—	—			ASTM A369 Grade FPB
bal	.15	—	—	.55	—	.55	.30	.04	.04	—	—	—	—			ASTM A369 Grade FPI
bal	.15	—	.65	.55	—	.45	.20	.04	.04	—	—	—	—			ASTM A369 Grade PF2
bal	.10	—	1.00	.55	—	.45	.40	.04	.04	—	—	—	—			ASTM A369 Grade FP12
bal	.10	—	1.25	.55	—	.45	.75	.03	.03	—	—	—	—			ASTM A369 Grade FP11
bal	.10	—	2.00	.55	—	.45	.40	.03	.03	—	—	—	—			ASTM A369 Grade FP3b

COMPOSITION, %																MATERIAL DESIGNATION
Fe	C	Ni	Cr	Mo	V	Mn	Si	P	S	Pb	Co	Ti	Al	—	—	Other	
3. CARBON AND FERRITIC ALLOY STEELS (HIGH TEMPERATURE SERVICE) (continued)																	
bal	.10	—	2.30	1.00	—	.45	.40	.03	.03	—	—	—	—				ASTM A369 Grade FP22
bal	.10	—	3.00	1.00	—	.45	.40	.03	.03	—	—	—	—				ASTM A369 Grade FP21
bal	.10	—	5.00	.55	—	.45	.40	.03	.03	—	—	—	—				ASTM A369 Grade FP5
bal	.10	—	7.00	.55	—	.45	.75	.03	.03	—	—	—	—				ASTM A369 Grade FP7
bal	.10	—	9.00	1.00	—	.45	.75	.03	.03	—	—	—	—				ASTM A369 Grade FP9
4. FREE MACHINING ALLOY STEELS, WROUGHT — Medium Carbon Resulfurized																	
bal	.40	—	1.00	.20	—	.90	.25	.03	.10	—	—	—	—				4140
bal	.40	—	1.00	.20	—	.90	.25	.03	.10	—	—	—	—			.04Se	4140Se
bal	.42	—	1.00	.20	—	.90	.25	.03	.10	—	—	—	—			.04Te	4142Te
bal	.45	—	1.00	.20	—	.90	.25	.03	.10	—	—	—	—			.04Se	4145Se
bal	.47	—	1.00	.20	—	.90	.25	.03	.10	—	—	—	—			.04Te	4147Te
bal	.50	—	1.00	.20	—	.90	.25	.03	.10	—	—	—	—				4150
4. FREE MACHINING ALLOY STEELS, WROUGHT — Medium and High Carbon Leaded																	
bal	.30	—	.95	.20	—	.50	.25	.03	.04	.25	—	—	—				41L30
bal	.40	—	1.00	.20	—	.85	.25	.03	.10	.25	—	—	—				41L40
bal	.45	—	1.00	.20	—	.85	.25	.03	04	.25	—	—	—				41L45
bal	.47	—	1.00	.20	—	.85	.25	.03	.04	.25	—	—	—				41L47
bal	.50	—	1.00	.20	—	.85	.25	.03	.04	.30	—	—	—				41L50
bal	.32	—	.90	—	—	.70	.25	.03	.04	.25	—	—	—				51L32
bal	1.00	—	1.50	—	—	.35	.25	.02	.02	.25	—	—	—				52L100
bal	.20	.60	.50	.20	—	.80	.25	.03	.04	.25	—	—	—				86L20
bal	.40	.60	.50	.20	—	.85	.25	.03	.04	.25	—	—	—				86L40
bal	.40	1.65	.80	.25	—	.70	.25	.03	.04	.25	—	—	—				43L40

COMPOSITION, %																MATERIAL DESIGNATION
Fe	C	Ni	Cr	Mo	V	Mn	Si	P	S	Pb	Co	Ti	Al	—	—	Other	
5. ALLOY STEELS, WROUGHT — Low Carbon																	
bal	.15	—	.40	—	—	.40	.25	.03	.04	—	—	—	—				5015
bal	.15	—	.80	—	—	.80	.25	.03	.04	—	—	—	—				5115
bal	.18	—	.50	.10	—	.80	.25	.03	.04	—	—	—	—				4118
bal	.18	—	.60	—	.10	.60	.25	.03	.04	—	—	—	—				6118
bal	.19	—	.55	—	—	.55	.25	.03	.04	—	—	—	—				4419
bal	.20	—	.80	—	—	.80	.25	.03	.04	—	—	—	—				5120
bal	.12	—	—	.20	—	.90	.25	.03	.04	—	—	—	—				4012
bal	.22	—	—	.40	—	.80	.25	.03	.04	—	—	—	—				4422
bal	.23	—	—	.25	—	.80	.25	.03	.04	—	—	—	—				4023
bal	.24	—	—	.25	—	.80	.25	.03	.04	—	—	—	—				4024
bal	.15	1.80	—	.25	—	.55	.25	.03	.04	—	—	—	—				4615
bal	.15	3.50	—	.25	—	.50	.25	.03	.04	—	—	—	—				4815
bal	.17	1.80	—	.25	—	.55	.25	.03	.04	—	—	—	—				4617
bal	.17	3.50	—	.25	—	.50	.25	.03	.04	—	—	—	—				4817
bal	.20	1.80	—	.25	—	.55	.25	.03	.04	—	—	—	—				4620
bal	.20	3.50	—	.25	—	.60	.25	.03	.04	—	—	—	—				4820
bal	.21	1.80	—	.25	—	.80	.25	.03	.04	—	—	—	—				4621
bal	.10	3.30	1.20	.10	—	.55	.25	.02	.02	—	—	—	—				9310
bal	.15	.30	.40	.10	—	.80	.25	.03	.04	—	—	—	—				8115
bal	.15	.50	.50	.10	—	.90	.25	.03	.04	—	—	—	—			.0005B min.	94B15
bal	.17	.50	.50	.10	—	.90	.25	.03	.04	—	—	—	—			.0005B min.	94B17
bal	.17	.60	.50	.20	—	.80	.25	.03	.04	—	—	—	—				8617
bal	.18	1.10	.50	.35	—	.80	—	—	—	—	—	—	—				4718
bal	.20	.60	.50	.20	—	.80	.25	.03	.04	—	—	—	—				8620
bal	.20	1.10	.50	.20	—	.60	.25	.03	.04	—	—	—	—				4720
bal	.20	1.80	.50	.25	—	.55	.25	.03	.04	—	—	—	—				4320
bal	.22	.60	.50	.20	—	.80	.25	.03	.04	—	—	—	—				8622
bal	.22	.60	.50	.35	—	.90	.25	.03	.04	—	—	—	—				8822

COMPOSITION, %																MATERIAL DESIGNATION
Fe	C	Ni	Cr	Mo	V	Mn	Si	P	S	Pb	Co	Tl	Al	—	—	Other	
5. ALLOY STEELS, WROUGHT — Medium Carbon																	
bal	.30	—	—	—	—	1.75	.25	.03	.04	—	—	—	—				1330
bal	.35	—	—	—	—	1.80	.25	.03	.04	—	—	—	—				1335
bal	.40	—	—	—	—	1.80	.25	.03	.04	—	—	—	—				1340
bal	.45	—	—	—	—	1.80	.25	.03	.04	—	—	—	—				1345
bal	.55	—	—	—	—	.85	2.00	.03	.04	—	—	—	—				9255
bal	.60	—	—	—	—	.90	2.00	.03	.04	—	—	—	—				9260
bal	.30	—	1.00	—	—	.70	.25	.03	.04	—	—	—	—				5130
bal	.32	—	.90	—	—	.70	.25	.03	.04	—	—	—	—				5132
bal	.35	—	1.00	—	—	.70	.25	.03	.04	—	—	—	—				5135
bal	.40	—	.50	—	—	.90	.25	.03	.04	—	—	—	—			.0005B min.	50B40
bal	.40	—	.80	—	—	.80	.25	.03	.04	—	—	—	—				5140
bal	.44	—	.50	—	—	.90	.25	.03	.04	—	—	—	—			.0005B min.	50B44
bal	.45	—	.80	—	—	.80	.25	.03	.04	—	—	—	—				5145
bal	.46	—	.30	—	—	.90	.25	.03	.04	—	—	—	—				5046
bal	.46	—	.30	—	—	.90	.25	.03	.04	—	—	—	—			.0005B min.	50B46
bal	.47	—	1.00	—	—	.85	.25	.03	.04	—	—	—	—				5147
bal	.50	—	.50	—	—	.90	.25	.03	.04	—	—	—	—			.0005B min.	50B50
bal	.50	—	.80	—	—	.80	.25	.03	.04	—	—	—	—				5150
bal	.50	—	1.00	—	.15	.80	.25	.03	.04	—	—	—	—				6150
bal	.54	—	.70	—	—	.70	1.40	.03	.04	—	—	—	—				9254
bal	.55	—	.80	—	—	.80	.25	.03	.04	—	—	—	—				5155
bal	.60	—	.50	—	—	.90	.25	.03	.04	—	—	—	—				5060
bal	.60	—	.50	—	—	.90	.25	.03	.04	—	—	—	—			.0005B min.	50B60
bal	.60	—	.80	—	—	.90	.25	.03	.04	—	—	—	—				5160
bal	.60	—	.80	—	—	.90	.25	.03	.04	—	—	—	—			.0005B min.	51B60
bal	.27	—	—	.25	—	.80	.25	.03	.04	—	—	—	—				4027
bal	.27	—	—	.40	—	.80	.25	.03	.04	—	—	—	—				4427
bal	.28	—	—	.25	—	.80	.25	.03	.04	—	—	—	—				4028
bal	.32	—	—	.25	—	.80	.25	.03	.04	—	—	—	—				4032

COMPOSITION, %																	MATERIAL DESIGNATION
Fe	C	Ni	Cr	Mo	V	Mn	Si	P	S	Pb	Co	Ti	Al	—	—	Other	
5. ALLOY STEELS, WROUGHT — Medium Carbon (continued)																	
bal	.37	—	—	.25	—	.80	.25	.03	.04	—	—	—	—				4037
bal	.42	—	—	.25	—	.80	.25	.03	.04	—	—	—	—				4042
bal	.47	—	—	.25	—	.80	.25	.03	.04	—	—	—	—				4047
bal	.26	.90	—	.20	—	.55	.25	.03	.04	—	—	—	—				4626
bal	.30	—	.95	.20	—	.50	.25	.03	.04	—	—	—	—				4130
bal	.35	—	1.00	.20	—	.80	.25	.03	.04	—	—	—	—				4135
bal	.37	—	1.00	.20	—	.80	.25	.03	.04	—	—	—	—				4137
bal	.40	—	1.00	.20	—	.90	.25	.03	.04	—	—	—	—				4140
bal	.42	—	1.00	.20	—	.90	.25	.03	.04	—	—	—	—				4142
bal	.45	—	1.00	.20	—	.90	.25	.03	.04	—	—	—	—				4145
bal	.47	—	1.00	.20	—	.90	.25	.03	.04	—	—	—	—				4147
bal	.50	—	1.00	.20	—	.90	.25	.03	.04	—	—	—	—				4150
bal	.61	—	.80	.30	—	.90	.25	.03	.04	—	—	—	—				4161
bal	.25	.60	.50	.20	—	.80	.25	.03	.04	—	—	—	—				8625
bal	.27	.60	.50	.20	—	.80	.25	.03	.04	—	—	—	—				8627
bal	.30	.50	.40	.12	—	.90	.25	.03	.04	—	—	—	—			.0005B min.	94B30
bal	.30	.60	.50	.20	—	.80	.25	.03	.04	—	—	—	—				8630
bal	.37	.60	.50	.20	—	.90	.25	.03	.04	—	—	—	—				8637
bal	.40	.60	.50	.20	—	.90	.25	.03	.04	—	—	—	—				8640
bal	.40	.60	.50	.30	—	.90	.25	.03	.04	—	—	—	—				8740
bal	.40	1.80	.80	.20	—	.70	.25	.03	.04	—	—	—	—				4340
bal	.42	.60	.50	.20	—	.90	.25	.03	.04	—	—	—	—				8642
bal	.42	.60	.50	.25	—	.90	.25	.03	.04	—	—	—	—				8742
bal	.45	.30	.45	.12	—	1.00	.25	.03	.04	—	—	—	—			.0005B min.	81B45
bal	.45	.60	.50	.20	—	.90	.25	.03	.04	—	—	—	—				8645
bal	.45	.60	.50	.20	—	.90	.25	.03	.04	—	—	—	—			.0005B min.	86B45
bal	.50	.60	.50	.20	—	.90	.25	.03	.04	—	—	—	—				8650
bal	.55	.60	.50	.20	—	.90	.25	.03	.04	—	—	—	—				8655
bal	.60	.60	.50	.20	—	.90	.25	.03	.04	—	—	—	—				8660

COMPOSITION, %																	MATERIAL DESIGNATION
Fe	C	Ni	Cr	Mo	V	Mn	Si	P	S	Pb	Co	Ti	Al	—	—	Other	
5. ALLOY STEELS, WROUGHT — High Carbon																	
bal	1.00	—	.50	—	—	.35	.25	.02	.02	—	—	—	—				50100
bal	1.00	—	1.00	—	—	.35	.25	.02	.02	—	—	—	—				51100
bal	1.00	—	1.50	—	—	.35	.25	.02	.02	—	—	—	—				52100
bal	.80	—	4.10	4.25	1.00	.30	.20	.01	.01	—	—	—	—				M-50
6. HIGH STRENGTH STEELS, WROUGHT																	
bal	.20	9.00	.75	1.00	.10	.30	.10	—	—	—	4.00	—	—				HP9-4-20
bal	.25	9.00	.45	.45	—	.20	.10	—	—	—	4.00	—	—				HP9-4-25
bal	.30	9.00	1.00	1.00	.10	.20	.10	—	—	—	4.00	—	—				HP9-4-30
bal	.32	1.80	.90	.43	.08	.90	.30	—	—	—	—	—	—				4330V
bal	.35	—	5.00	1.50	.40	.30	1.00	—	—	—	—	—	—				H11
bal	.35	—	5.00	1.50	1.00	.30	1.00	—	—	—	—	—	—				H13
bal	.40	1.80	.80	.20	—	70	.30	—	—	—	—	—	—				4340
bal	.40	75	.90	.60	.02	.90	.60	—	—	—	—	—	—			.0007B	98BV40
bal	.40	1.80	.80	.40	.08	—	1.60	—	—	—	—	—	—				4340SI
bal	.45	9.00	.30	.30	—	.20	.10	—	—	—	4.00	—	—				HP9-4-45
bal	.45	.55	1.05	1.00	.07	.75	.25	—	—	—	—	—	—				D6ac
bal	.45	1.80	.80	40	.08	.80	1.60	—	—	—	—	—	—				300M
7. MARAGING STEELS, WROUGHT																	
bal	.13	9.00	—	—	—	.90	.23	—	—	—	—	—	—				120 Grade
bal	.02	12.00	4.80	3.00	—	—	—	—	—	—	—	—	—				180 Grade
bal	.01	17.50	—	4.60	—	.10	.10	—	—	—	11.80	1.80	.15				350 Grade
bal	.03	18.00	—	4.80	—	.10	.10	—	—	—	7.50	.40	.10				250 Grade
bal	.03	18.00	—	4.30	—	.10	.10	.01	.01	—	8.00	.20	.10				ASTM A538 Grade A
bal	.03	18.00	—	4.80	—	.10	.10	.01	.01	—	8.00	.40	.10				ASTM A538 Grade B
bal	.03	18.00	—	3.25	—	.10	.10	—	—	—	8.50	.20	.10				200 Grade
bal	.03	18.50	—	4.80	—	.10	.10	—	—	—	9.00	.65	.10				300 Grade
bal	.03	18.50	—	5.00	—	.10	.10	.01	.01	—	9.00	.75	.10				ASTM A538 Grade C

COMPOSITION, %																	
Fe	C	W	Mo	Cr	Co	V	Mn	Ni	Si	—	—	—	—	—	—	Other	MATERIAL DESIGNATION
8. TOOL STEELS, WROUGHT — High Speed																	
bal	.85	—	8.00	4.00	—	2.00	—	—	—								M10
bal	.85	1.50	8.50	4.00	—	1.00	—	—	—								M1
bal	.85	6.00	5.00	4.00	—	2.00	—	—	—								M2
bal	1.00	1.75	8.75	4.00	—	2.00	—	—	—								M7
bal	1.05	6.00	5.00	4.00	—	2.40	—	—	—								M3 Class 1
bal	1.20	6.00	5.00	4.00	—	3.00	—	—	—								M3 Class 2
bal	1.30	5.50	4.50	4.00	—	4.00	—	—	—								M4
bal	.75	18.00	—	4.00	—	1.00	—	—	—								T1
bal	.80	13.00	—	4.00	—	2.00	—	—	—								T2
bal	.75	14.00	—	4.00	5.00	2.00	—	—	—								T8
bal	.75	18.00	—	4.00	5.00	1.00	—	—	—								T4
bal	.80	18.00	—	4.00	8.00	2.00	—	—	—								T5
bal	.80	20.00	—	4.50	12.00	1.50	—	—	—								T6
bal	1.50	12.00	—	4.00	5.00	5.00	—	—	—								T15
bal	.80	2.00	8.00	4.00	5.00	1.25	—	—	—								M30
bal	.80	4.00	5.00	4.00	12.00	1.50	—	—	—								M6
bal	.80	6.00	5.00	4.00	8.00	2.00	—	—	—								M36
bal	.90	1.50	9.50	4.00	8.00	1.15	—	—	—								M33
bal	.90	2.00	8.00	4.00	8.00	2.00	—	—	—								M34
bal	1.10	1.50	9.50	3.75	8.00	1.15	—	—	—								M42
bal	1.10	1.50	9.50	3.75	5.00	1.25	—	—	—								M47
bal	1.10	6.75	3.75	4.25	5.00	2.00	—	—	—								M41
bal	1.15	5.25	6.25	4.25	12.00	2.00	—	—	—								M44
bal	1.20	2.75	8.00	3.75	8.25	1.60	—	—	—								M43
bal	1.25	2.00	8.25	4.00	8.25	3.20	—	—	—								M46

COMPOSITION, %											MATERIAL DESIGNATION
Fe	C	W	Mo	Cr	Co	V	Mn	Ni	Si	Other	
8. TOOL STEELS, WROUGHT — Hot Work											
bal	.35	—	1.50	5.00	—	.40	—	—	—		H11
bal	.35	—	1.50	5.00	—	1.00	—	—	—		H13
bal	.40	—	2.50	3.25	—	.40	—	—	—		H10
bal	.25	15.00	—	4.00	—	—	—	—	—		H25
bal	.30	12.00	—	12.00	—	—	—	—	—		H23
bal	.35	11.00	—	2.00	—	—	—	—	—		H22
bal	.35	9.00	—	3.50	—	—	—	—	—		H21
bal	.40	5.00	—	5.00	—	—	—	—	—		H14
bal	.45	15.00	—	3.00	—	—	—	—	—		H24
bal	.50	18.00	—	4.00	—	1.00	—	—	—		H26
bal	.40	4.25	—	4.25	4.25	2.00	—	—	—		H19
bal	.35	1.50	1.50	5.00	—	.40	—	—	—		H12
bal	.60	6.00	5.00	4.00	—	2.00	—	—	—		H42
8. TOOL STEELS, WROUGHT — Cold Work											
bal	.50	—	1.40	5.00	—	1.00	—	1.50	—		A9
bal	.55	1.25	1.25	5.00	—	—	—	—	—		A8
bal	.70	—	1.25	1.00	—	—	2.00	—	—		A6
bal	.90	.50	—	.50	—	—	1.00	—	—		O1
bal	.90	—	—	—	—	—	1.60	—	—		O2
bal	1.00	—	1.00	1.00	—	—	2.00	—	—		A4
bal	1.00	—	1.00	5.00	—	—	—	—	—		A2
bal	1.20	1.75	—	.75	—	—	—	—	—		C7
bal	1.25	—	1.00	5.00	—	1.00	—	—	—		A3
bal	1.35	—	1.50	—	—	—	1.80	1.80	1.25		A10
bal	1.45	—	.25	—	—	—	.30	—	1.00		O6
bal	1.50	—	1.00	12.00	—	1.00	—	—	—		D2
bal	1.50	—	1.00	12.00	3.00	—	—	—	—		D5
bal	2.25	—	—	12.00	—	—	—	—	—		D3

COMPOSITION, %																	
Fe	C	W	Mo	Cr	Co	V	Mn	Ni	Si	—	—	—	—	—	—	Other	MATERIAL DESIGNATION
8. TOOL STEELS, WROUGHT — Cold Work (continued)																	
bal	2.25	—	1.00	12.00	—	—	—	—	—								D4
bal	2.25	1.00	1.00	5.25	—	4.75	—	—	—								A4
bal	2.35	—	1.00	12.00	—	4.00	—	—	—								D7
8. TOOL STEELS, WROUGHT — Shock Resisting																	
bal	.45	—	.40	1.50	—	—	1.40	—	2.25								S6
bal	.50	—	1.40	3.25	—	—	—	—	—								S7
bal	.50	2.50	—	1.50	—	—	—	—	—								S1
bal	.50	—	.50	—	—	—	—	—	1.00								S2
bal	.55	—	.40	—	—	—	.80	—	2.00								S5
8. TOOL STEELS, WROUGHT — Mold																	
bal	.07	—	.20	2.00	—	—	—	.50	—								P2
bal	.07	—	.75	5.00	—	—	—	—	—								P4
bal	.10	—	—	2.25	—	—	—	—	—								P5
bal	.10	—	—	1.50	—	—	—	3.50	—								P6
bal	.20	—	—	—	—	—	—	4.00	—							1.20Al	P21
bal	.35	—	.40	1.70	—	—	—	—	—								P20
8. TOOL STEELS, WROUGHT — Special Purpose																	
bal	.70	—	—	.70	—	—	—	1.50	—								L6
bal	.80	—	—	1.00	—	.20	—	—	—								L2
bal	1.00	—	.40	1.50	—	—	.35	—	.30								L7
bal	1.00	1.25	—	—	—	—	—	—	—								F1
bal	1.25	3.50	—	—	—	—	—	—	—								F2
8. TOOL STEELS, WROUGHT — Water Hardening																	
bal	.60	—	—	—	—	—	—	—	—								W1
bal	.60	—	—	—	—	.25	—	—	—								W2
bal	.80	—	—	.15	—	—	.35	—	.35								SAE J438b Type W108
bal	.90	—	—	.15	—	—	.35	—	.35								SAE J438b Type W109

COMPOSITION, %																	MATERIAL DESIGNATION
Fe	C	W	Mo	Cr	Co	V	Mn	Ni	Si	—	—	—	—	—	—	Other	
8. TOOL STEELS, WROUGHT — Water Hardening (continued)																	
bal	.90	—	—	.15	—	.25	.35	—	.35								SAE J438b Type W209
bal	1.05	—	—	.15	—	—	.35	—	.35								SAE J438b Type W110
bal	1.05	—	—	.15	—	.25	.35	—	.35								SAE J438b Type W210
bal	1.05	—	—	.15	—	.45	.35	—	.35								SAE J438b Type W310
bal	1.10	—	—	.50	—	—	—	—	—								W5
bal	1.20	—	—	.15	—	—	.35	—	.35								SAE J438b Type W112

COMPOSITION, %																	MATERIAL DESIGNATION
Fe	C	Ni	Cr	Mo	V	Mn	Si	P	S	Al	Cu	—	—	—	—	Other	
9. NITRIDING STEELS, WROUGHT																	
bal	.23	3.50	1.25	.25	—	.55	.30	—	—	1.00	—						Nitralloy N
bal	.25	—	—	.60	—	.55	.30	—	—	1.00	—						Nitralloy 225
bal	.25	—	1.15	.20	—	.55	.30	—	—	.90	—						Nitralloy 125
bal	.30	—	—	.80	—	.50	.30	—	—	1.25	—						Nitralloy 230
bal	.35	—	1.15	.20	—	.55	.30	—	—	.90	—						Nitralloy 135
bal	.35	—	1.25	.20	—	.80	.30	—	—	1.00	—					.20Se	Nitralloy EZ
bal	.40	—	1.60	.38	—	.55	.30	—	—	1.05	—						Nitrex 1
bal	.42	—	1.60	.37	—	.55	.30	—	—	1.00	—						Nitralloy 135 Mod.
10. ARMOR PLATE, SHIP PLATE, AIRCRAFT PLATE, WROUGHT																	
bal	.10	.50	.30	.07	.10	.30	.20	.02	.02	—	—						MIL-S-12560
bal	.11	10.00	2.00	1.00	—	—	—	—	—	—	—					10.00Co	HY180
bal	.15	3.00	1.40	.40	.03	.25	.25	.02	.02	—	.25					.02Ti	MIL-S-16216 (HY80)
bal	.18	3.00	1.40	.40	—	.25	.25	.02	.02	—	—						HY80
bal	.16	3.25	1.40	.40	.03	.25	.25	.02	.02	—	.25					.02Ti	MIL-S-16216 (HY100)
bal	.20	3.25	1.40	.40	—	.25	.25	.02	.02	—	—						HY100

COMPOSITION, %																	
Fe	C	Ni	Cr	Mo	V	Mn	Si	P	S	Al	Cu	—	—	—	—	Other	MATERIAL DESIGNATION
11. STRUCTURAL STEELS, WROUGHT*																	
bal	.06	1.00	—	—	—	.35	—	—	—	—	1.50					V	85
bal	.12	—	—	—	—	.75	—	—	—	—	—					Cb-V	35
bal	.15	—	.60	.30	—	1.20	—	—	—	—	—					B-Zr	90
bal	.15	—	—	.30	—	1.30	—	—	—	—	—					B	150
bal	.16	.80	.50	.30	—	.80	—	—	—	—	.20					V-B	145
bal	.16	3.00	.50	.50	—	.80	—	—	—	—	.20					V-B	140
bal	.18	1.30	1.00	.30	—	.60	—	—	—	—	—					V-B-Zr	100
bal	.18	1.50	.70	.30	—	1.00	—	—	—	—	—					V	80
bal	.18	—	.70	.30	—	1.00	—	—	—	—	—					B-Zr	110
bal	.20	—	.70	.20	—	.80	—	—	—	—	—					Zr	165
bal	.20	—	—	—	—	.90	—	—	—	—	—						30
bal	.21	—	—	—	—	1.25	—	—	—	—	—					Cb-V	42
bal	.22	—	—	—	—	1.25	—	—	—	—	—					Cb-V	45
bal	.23	—	.50	.20	—	1.20	—	—	—	—	.20					V-B	135
bal	.23	.60	.60	—	—	1.25	—	—	—	—	.30						50
bal	.25	—	—	—	—	1.35	—	—	—	—	—					Cb-V	55
bal	.26	—	—	—	—	1.35	—	—	—	—	—					Cb-V	60
bal	.26	—	—	—	—	1.35	—	—	—	—	—					Cb-V	65
bal	.26	—	—	—	—	1.40	—	—	—	—	—					Cb-V	70
bal	.26	.31	—	.50	—	1.00	—	—	—	—	—					V	75
bal	.28	—	—	.20	—	1.50	—	—	—	—	.20					B	160
bal	.28	—	—	.20	—	1.50	—	—	—	—	.20					B	185
bal	.28	—	—	.20	—	1.50	—	—	—	—	.20					B	210

*In this handbook, Structural Steels are designated by yield strength in units of 1000 psi. For example, 50 means a steel with 50,000 psi yield strength. Chemical compositions are therefore approximate so as to apply to a variety of trade name steels.

COMPOSITION, %																	
Fe	C	Cr	Ni	Mo	Mn	Si	P	S	Al	Cu	—	—	—	—	—	Other	MATERIAL DESIGNATION
12. FREE MACHINING STAINLESS STEELS, WROUGHT — Ferritic																	
bal	.12	17.00	—	.60*	1.25	1.00	.06	.15	—	—							430F
bal	.12	17.00	—	—	1.25	1.00	.06	.06	—	—						.15Se min.	430F Se
12. FREE MACHINING STAINLESS STEEL S, WROUGHT — Austenitic																	
bal	.08	17.00	6.00	.50	6.50	1.00	.04	.35	—	2.00							203EZ
bal	.15	18.00	9.00	.60*	2.00	1.00	.20	.15	—	—							303
bal	.15	18.00	9.00	—	2.00	1.00	.20	.06	—	—						.15Se min.	303Se
bal	.15	18.00	9.00	.50	2.00	1.00	.05	.16	.80	—							303MA
bal	.15	18.00	9.00	.60	2.00	1.00	.04	.25	—	—						.25Pb	303Pb
bal	.15	18.00	8.50	.60	4.50	1.00	.20	.15	—	—							303 Plus X
12. FREE MACHINING STAINLESS STEELS, WROUGHT — Martensitic																	
bal	.15	13.00	—	.60*	1.25	1.00	.06	.15	—	—							416
bal	.15	13.00	—	—	1.25	1.00	.06	.06	—	—						.15Se min.	416Se
bal	.15	13.00	—	.60	2.50	1.00	.06	.15	—	—							416 Plus X
bal	.15	13.00	—	.60*	1.25	1.00	.06	.15	—	—							420F
bal	.40	13.00	—	—	1.25	1.00	.06	.06	—	—						.15Se min.	420F Se
bal	1.20	17.00	—	.75*	1.25	1.00	.06	.15	—	—							440F
bal	1.20	17.00	—	—	1.25	1.00	.06	.06	—	—						.15Se min.	440F Se
13. STAINLESS STEELS, WROUGHT — Ferritic																	
bal	.08	11.00	.50	—	1.00	1.00	.04	.04	—	—						.75Ti	409
bal	.08	13.00	—	—	1.00	1.00	.04	.03	.20	—							405
bal	.12	15.00	—	—	1.00	1.00	.04	.03	—	—							429
bal	.12	17.00	—	—	1.00	1.00	.04	.03	—	—							430
bal	.12	17.00	—	1.00	1.00	1.00	.04	.03	—	—							434
bal	.12	17.00	—	1.00	1.00	1.00	.04	.03	—	—						.70Cb + Ta	436
bal	.20	20.00	—	—	1.00	1.00	.04	.03	—	—							442
bal	.20	25.00	—	—	1.50	1.00	.04	.03	—	—						.25N	446

*Optional.

COMPOSITION, %																	
Fe	C	Cr	Ni	Mo	Mn	Si	P	S	Al	Cu	—	—	—	—	—	Other	MATERIAL DESIGNATION
13. STAINLESS STEELS, WROUGHT — Austenitic																	
bal	.03	17.00	12.00	2.50	2.00	1.00	.04	.03	—	—							316L
bal	.03	19.00	10.00	—	2.00	1.00	.04	.03	—	—							304L
bal	.06	22.00	12.50	2.50	6.00	1.00	.04	.03	—	—						.30N, .20Cb, .20V	Nitronic 50
bal	.08	12.50	15.00	—	2.00	1.00	.04	.03	—	—							385
bal	.08	16.00	18.00	—	2.00	1.00	.04	.03	—	—							384
bal	.08	17.00	12.00	2.50	2.00	1.00	.04	.03	—	—							316
bal	.08	18.00	10.50	—	2.00	1.00	.04	.03	—	—						Ti 5xC min.	321
bal	.08	18.00	11.00	—	2.00	1.00	.04	.03	—	—						Cb + Ta 10xC min.	347
bal	.08	18.00	11.00	—	2.00	1.00	.04	.03	—	—						Cb + Ta 10xC min., .10Ta, .20Co	348
bal	.08	18.00	3.00	—	14.50	1.00	.06	.03	—	—						.30N	Nitronic 33
bal	.08	19.00	13.00	3.50	2.00	1.00	.04	.03	—	—							317
bal	.08	19.00	9.00	—	2.00	1.00	.04	.03	—	—							304
bal	.08	20.00	11.00	—	2.00	1.00	.04	.03	—	—							308
bal	.08	20.00	6.50	—	10.00	1.00	.06	.03	—	—						.30N	Nitronic 40
bal	.08	23.00	13.50	—	2.00	1.00	.04	.03	—	—							309S
bal	.08	25.00	21.00	—	2.00	1.50	.04	.03	—	—							310S
bal	.10	17.00	8.50	—	9.00	4.50	—	—	—	—						.10N	Nitronic 60
bal	.12	18.00	12.00	—	2.00	1.00	.04	.03	—	—							305
bal	.15	15.50	35.00	—	2.00	1.50	.04	.04	—	—							330
bal	.15	18.00	1.50	—	14.00	1.00	.06	.03	—	—						.35N	Nitronic 32
bal	.15	17.00	4.50	—	7.50	1.00	.06	.03	—	—							201
bal	.15	17.00	7.00	—	2.00	1.00	.04	.03	—	—							301
bal	.15	18.00	5.00	—	10.00	1.00	.06	.03	—	—						.25N	202
bal	.15	18.00	9.00	—	2.00	1.00	.04	.03	—	—							302
bal	.15	18.00	9.00	—	2.00	3.00	.04	.03	—	—							302B
bal	.20	23.00	13.50	—	2.00	1.00	.04	.03	—	—							309
bal	.25	25.00	21.00	—	2.00	3.00	.04	.03	—	—							314
bal	.25	25.00	21.00	—	2.00	1.50	.04	.03	—	—							310

COMPOSITION, %																	
Fe	C	Cr	Ni	Mo	Mn	Si	P	S	Al	Cu	—	—	—	—	—	Other	MATERIAL DESIGNATION
13. STAINLESS STEELS, WROUGHT — Martensitic																	
bal	.10	5.00	—	.55	1.00	1.00	.04	.03	—	—							502
bal	.10	5.00	—	.55	1.00	1.00	.04	.03	—	—							501
bal	.15	12.25	—	—	1.00	.50	.04	.03	—	—							403
bal	.15	12.50	—	—	1.00	1.00	.04	.03	—	—							410
bal	.15	12.50	2.00	—	1.00	1.00	.04	.03	—	—							414
bal	.15	13.00	—	—	1.00	1.00	.04	.03	—	—							420
bal	.20	13.00	2.00	.50	.50	.50	—	—	—	—						3.00W	Greek Ascoloy
bal	.20	16.00	2.00	—	1.00	1.00	.04	.03	—	—							431
bal	.25	13.00	.75	1.00	1.00	1.00	.04	.03	—	—						1.00W, .35V	422
bal	.75	17.00	—	.75	1.00	1.00	.04	.03	—	—							440A
bal	.95	17.00	—	.75	1.00	1.00	.04	.03	—	—							440B
bal	1.20	17.00	—	.75	1.00	1.00	.04	.03	—	—							440C
14. PRECIPITATION HARDENING STAINLESS STEELS, WROUGHT																	
bal	.03	12.00	8.50	—	.25	.25	—	—	—	2.00						1.30Ti, 30Co	Custom 455
bal	.05	11.50	4.50	—	.20	.15	—	—	—	—						.30Ti	AM-363
bal	.05	12.75	8.00	2.25	.10	.10	.01	.008	1.10	—							PH 13-8Mo
bal	.05	14.25	6.50	—	.05	.30	—	—	—	—						.75Ti	Almar 362 (AM-362)
bal	.05	14.50	8.00	2.50	1.00	1.00	.01	.01	1.10	—							PH 14-8Mo
bal	.05	15.00	4.50	—	1.00	1.00	.04	.03	—	3.50							15-5 PH
bal	.05	15.50	6.50	.75	.50	.50	.03	.03	—	1.50						Cb 8xC min.	Custom 450
bal	.05	16.50	4.50	—	1.00	1.00	.04	.03	—	4.00							17-4 PH
bal	.07	17.00	7.00	—	1.00	1.00	.04	.03	.20	—						.70Ti	Stainless W
bal	.08	16.00	7.00	—	1.00	1.00	—	—	1.00	—						.70Ti	16-6 PH
bal	.09	15.00	7.00	2.50	1.00	1.00	.04	.03	1.10	—							PH 15-7Mo
bal	.09	17.00	7.00	—	1.00	1.00	.04	.03	1.10	—							17-7 PH
bal	.10	17.00	4.50	3.00	1.00	.50	.04	.03	—	—							AM-350
bal	.12	16.00	14.00	2.50	.75	.50	.02	.01	—	3.00							17-14 Cu Mo
bal	.13	15.00	4.00	2.50	1.10	.75	.04	.03	—	—							AM-355

COMPOSITION, %																	MATERIAL DESIGNATION
Fe	C	Cr	Ni	Mo	Mn	Si	P	S	Al	Cu	—	—	—	—	—	Other	
14. PRECIPITATION HARDENING STAINLESS STEELS, WROUGHT (continued)																	
bal	.15	14.50	—	5.00	.02	.10	.005	.01	—	—						13.50Co, .50V	AFC-77
bal	.25	12.00	—	3.00	18.00	.25	.02	.02	—	—						.20B, .80V	AF-71
bal	.30	18.50	9.50	—	3.50	.50	.25	.25	—	—							HNM

COMPOSITION, %																	MATERIAL DESIGNATION
Fe	C	Ni	Cr	Mo	Mn	Si	P	S	—	—	—	—	—	—	—	Other	
15. CARBON STEELS, CAST — Low Carbon																	
bal	.10	—	—	—	.20	.55	.04	.05									1010
bal	.15	—	—	.55	.55	.30	.04	.04									ASTM A426 Grade CP1
bal	.20	—	—	—	.67	.38	.04	.05									1020
15. CARBON STEELS, CAST — Medium Carbon																	
bal	.25	—	—	—	.70	.60	.04	.04									ASTM A352 Grade LCA
bal	.25	—	—	—	1.20	.60	.04	.04									ASTM A352 Grade LCC
bal	.30	—	—	—	1.00	.60	.04	.04									ASTM A352 Grade LCB
bal	.30	—	—	—	.70	.45	.04	.05									1030
bal	.35	—	—	—	.70	.60	.03	.03									ASTM A356 Grade 1
bal	.40	—	—	—	.76	.50	.04	.05									1040
bal	.50	—	—	—	.70	.42	.04	.05									1050
16. ALLOY STEELS, CAST — Low Carbon																	
bal	.20	—	—	—	1.35	.45	.04	.04									1320
bal	.15	3.50	—	—	.65	.60	.04	.04									ASTM A352 Grade LC3
bal	.15	3.50	—	—	.75	.50	.04	.04									2315
bal	.15	4.50	—	—	.65	.60	.04	.04									ASTM A352 Grade LC4
bal	.20	3.40	—	—	.75	.50	.04	.04									2320
bal	.15	—	—	.55	.40	1.00	.03	.03									ASTM A426 Grade CP15
bal	.20	—	—	.20	1.30	.35	.04	.04									8020

COMPOSITION, %																	MATERIAL DESIGNATION
Fe	C	Ni	Cr	Mo	Mn	Si	P	S	—	—	—	—	—	—	—	Other	
16. ALLOY STEELS, CAST — Low Carbon (continued)																	
bal	.10	—	.90	.30	.75	.50	.04	.04									4110
bal	.15	—	.70	.55	.50	.30	.04	.04									ASTM A426 Grade CP2
bal	.15	—	1.00	.55	.50	.50	.04	.04									ASTM A426 Grade CP12
bal	.15	—	1.25	.55	.60	.60	.03	.03									ASTM A426 Grade CP11
bal	.15	—	2.50	1.10	.50	.60	.03	.03									ASTM A426 Grade CP22
bal	.15	—	3.00	.95	.50	.50	.03	.03									ASTM A426 Grade CP21
bal	.15	—	5.00	.55	.50	1.50	.03	.03									ASTM A426 Grade CP5b
bal	.15	—	5.50	.55	.50	.60	.03	.03									ASTM A426 Grade CP5
bal	.18	—	2.50	1.10	.60	.60	.04	.04									ASTM A217 Grade WC9
bal	.20	—	.98	.35	.75	.50	.04	.04									4120
bal	.20	1.80	.50	.25	.60	.50	.03	.04									4320
bal	.20	.60	.50	.20	.60	.50	.03	.04									8620
16. ALLOY STEELS, CAST — Medium Carbon																	
bal	*	*	*	*	*	*	.05	.06									ASTM A148 Grade 80-40
bal	*	*	*	*	*	*	.05	.06									ASTM A148 Grade 80-50
bal	*	*	*	*	*	*	.05	.06									ASTM A148 Grade 90-60
bal	*	*	*	*	*	*	.05	.06									ASTM A148 Grade 105-85
bal	*	*	*	*	*	*	.05	.06									ASTM A148 Grade 120-95
bal	*	*	*	*	*	*	.05	.06									ASTM A148 Grade 150-125
bal	*	*	*	*	*	*	.05	.06									ASTM A148 Grade 175-145
bal	.35	*	*	*	*	*	.05	.06									ASTM A486 Class 90
bal	.35	*	*	*	*	*	.05	.06									ASTM A486 Class 120
bal	.35	—	—	—	.90	.80	.05	.06									ASTM A486 Class 70
bal	.25	—	—	—	.75	.80	.05	.06									ASTM A27 Grade N1
bal	.35	—	—	—	.60	.80	.05	.06									ASTM A27 Grade N2
bal	.30	—	—	—	.60	.80	.05	.06									ASTM A27 Grade U-60-30
bal	.30	—	—	—	.60	.80	.05	.06									ASTM A27 Grade 60-30
bal	.30	—	—	—	.70	.80	.05	.06									ASTM A27 Grade 65-35

COMPOSITION, %																	
Fe	C	Ni	Cr	Mo	Mn	Si	P	S	—	—	—	—	—	—	—	Other	MATERIAL DESIGNATION
16. ALLOY STEELS, CAST — Medium Carbon (continued)																	
bal	.35	—	—	—	.70	.80	.05	.06									ASTM A27 Grade 70-36
bal	.25	—	—	—	1.20	.80	.05	.06									ASTM A27 Grade 70-40
bal	.25	—	—	—	.70	.60	.04	.04									ASTM A216 Grade WCA
bal	.30	—	—	—	1.00	.60	.04	.04									ASTM A216 Grade WCB
bal	.25	—	—	—	1.20	.60	.04	.04									ASTM A216 Grade WCC
bal	.30	—	—	—	1.50	.50	.04	.04									1330
bal	.40	—	—	—	1.55	.50	.04	.04									1340
bal	.25	2.50	—	—	.70	.60	.04	.04									ASTM A352 Grade LC2
bal	.25	3.45	—	—	.75	.45	.04	.04									2325
bal	.30	3.50	—	—	.75	.45	.04	.04									2330
bal	.30	—	—	.20	1.30	.35	.04	.04									8030
bal	.30	—	—	.20	1.30	.35	.04	.04								.003B	80B30
bal	.40	—	—	.20	1.20	.35	.04	.04									8040
bal	.30	—	—	.40	1.35	.35	.04	.04									8430
bal	.40	—	—	.40	1.60	.35	.04	.04									8440
bal	.25	—	—	.55	.70	.60	.04	.04									ASTM A217 Grade WC1
bal	.25	—	—	.55	.70	.60	.04	.04									ASTM A352 Grade LC1
bal	.25	—	—	.55	.70	.60	.03	.03									ASTM A356 Grade 2
bal	.45	—	—	—	.70	.80	.04	.04								.03V	ASTM A487 Class DN
bal	.30	—	—	—	1.00	.80	.04	.04								.08V	ASTM A487 Class 1N
bal	.30	—	—	—	1.00	.80	.04	.04								.08V	ASTM A487 Class 1Q
bal	.30	—	—	.20	1.20	.80	.04	.04								.03V	ASTM A487 Class 2N
bal	.30	—	—	.20	1.20	.80	.04	.04								.03V	ASTM A487 Class 2Q
bal	.25	—	.60	.50	.70	.60	.03	.03									ASTM A356 Grade 5
bal	.25	—	.75	.30	.65	.50	.04	.04									4125
bal	.30	—	.75	.20	.65	.50	.04	.04									4130
bal	.40	—	1.00	.20	.65	.50	.04	.04									4140
bal	.20	—	1.25	.55	.70	.60	.04	.04									ASTM A217 Grade WC6

COMPOSITION, %															MATERIAL DESIGNATION
Fe	C	Ni	Cr	Mo	Mn	Si	P	S	—	—	—	—	—	Other	
16. ALLOY STEELS, CAST — Medium Carbon (continued)															
bal	.20	—	1.25	.55	.70	.60	.03	.03							ASTM A356 Grade 6
bal	.20	—	2.25	1.00	.70	.60	.03	.03							ASTM A356 Grade 10
bal	.33	—	1.00	.25	.80	.80	.04	.04						.03V	ASTM A487 Class 9N
bal	.33	—	1.00	.25	.80	.80	.04	.04						.03V	ASTM A487 Class 9Q
bal	.20	—	1.00	1.10	.60	.60	.04	.04						.20V	ASTM A389 Grade C24
bal	.20	—	1.25	.55	.60	.60	.04	.04						.20V	ASTM A389 Grade C23
bal	.20	—	1.25	1.10	.80	.50	.03	.03						.10V	ASTM A356 Grade 8
bal	.20	—	1.25	1.10	.80	.50	.03	.03						.30V	ASTM A356 Grade 9
bal	.20	—	2.25	1.00	.80	.80	.04	.04						.03V	ASTM A487 Class 8N
bal	.20	—	2.25	1.00	.80	.80	.04	.04						.03V	ASTM A487 Class 8Q
bal	.25	.50	.60	.35	1.40	50	.04	.04							9525
bal	.30	.65	.60	.40	1.40	.50	04	.04							9530
bal	.30	.60	.50	.20	.85	.40	.04	.04							8630
bal	.40	.60	.50	.20	.85	.40	.04	.04							8640
bal	.35	.55	.60	.35	1.50	.50	.04	.04							9535
bal	.20	.90	.80	1.10	.60	.60	.04	.04							ASTM A217 Grade WC5
bal	.20	1.00	.70	.55	.70	.60	.04	.04							ASTM A217 Grade WC4
bal	.30	1.80	.65	.20	.75	.50	.04	.04							4330
bal	.40	1.80	.80	.30	.75	.50	.04	.04							4340
bal	.22	3.00	1.60	.50	.65	.50	.04	.04							ASTM A352 Grade LC2-1
bal	.30	.60	.60	.25	1.00	.80	.04	.04						.03V	ASTM A487 Class 4N
bal	.30	.60	.60	.25	1.00	.80	.04	.04						.03V	ASTM A487 Class 4Q
bal	.30	.60	.60	.25	1.00	.80	.04	.04						.03V	ASTM A487 Class 4QA
bal	.38	.60	.60	.35	1.50	.80	.04	.04						.03V	ASTM A487 Class 6N
bal	.38	.60	.60	.35	1.50	.80	.04	.04						.03V	ASTM A487 Class 6Q
bal	.20	.90	.60	.50	.80	.80	.04	.04						.08V, .004B, .35Cu	ASTM A487 Class 7Q
bal	.30	1.80	.75	.30	—	.80	.04	.04						.03V	ASTM A487 Class 10N
bal	.30	1.80	.75	.30	—	.80	.04	.04						.03V	ASTM A487 Class 10Q

COMPOSITION, %																	MATERIAL DESIGNATION
Fe	C	W	Mo	Cr	V	Si	Mn	—	—	—	—	—	—	—	—	Other	
17. TOOL STEELS, CAST																	
bal	.35	1.35	1.50	5.25	.35	1.50	.75										ASTM A597 Grade CH-12
bal	.36	—	1.50	5.25	1.00	1.50	.75										ASTM A597 Grade CH-13
bal	.60	—	.80	.35	.35	2.25	1.00										ASTM A597 Grade CS-5
bal	.95	.50	—	.70	.30	1.50	1.30										ASTM A597 Grade CO-1
bal	1.00	—	1.20	5.25	.35	1.50	.75										ASTM A597 Grade CA-2
bal	1.45	—	.95	12.00	.45	1.50	.75									3.00Co, .50Ni	ASTM A597 Grade CD-5
bal	1.50	—	.95	12.00	.70	1.50	1.00									.85Co	ASTM A597 Grade CD-2

COMPOSITION, %																	MATERIAL DESIGNATION
Fe	C	Cr	Ni	Mo	Mn	Si	P	S	Cu	—	—	—	—	—	—	Other	
18. STAINLESS STEELS, CAST — Ferritic																	
bal	.20	6.00	—	.55	.60	.75	.04	.04	—								ASTM A217 Grade C5
bal	.20	9.00	—	1.00	.50	1.00	.04	.04	—								ASTM A217 Grade C12
bal	.06	11.50	7.00	—	.50	1.00	.02	.02	—								ASTM A296 Grade CA6N
bal	.30	20.00	2.00	—	1.00	1.50	.04	.04	—								ASTM A296 Grade CB-30
bal	.50	28.00	4.00	—	1.00	1.50	.04	.04	—								ASTM A296 Grade CC-50
bal	.30	29.00	9.00	—	1.50	2.00	.04	.04	—								ASTM A296 Grade CE-30
bal	.06	13.00	4.00	.80	1.00	1.00	.04	.03	—								ASTM A296 Grade CA-6NM
bal	.06	13.00	4.00	.80	1.00	1.00	.04	.03	—								ASTM A487 Class CA6NM
bal	.04	26.00	5.50	2.00	1.00	1.00	.04	.04	3.00								ASTM A296 Grade CD4MCu
bal	.30	28.00	4.00	.50	1.00	1.50	.04	.04	—								ASTM A608 Grade HC30
bal	.50	28.00	4.00	.50	1.00	2.00	.04	.04	—								ASTM A297 Grade HC
18. STAINLESS STEELS, CAST — Austenitic																	
bal	.03	19.00	9.00	—	1.50	2.00	.04	.04	—								ASTM A296 Grade CF-3
bal	.03	19.00	9.00	—	1.50	2.00	.04	.04	—								ASTM A351 Grade CF-3
bal	.03	19.00	9.00	—	1.50	2.00	.04	.04	—								ASTM A351 Grade CF-3A
bal	.03	19.00	9.00	—	1.50	2.00	.04	.04	—								ASTM A451 Grade CPF3

COMPOSITION, %																	MATERIAL DESIGNATION	
Fe	C	Cr	Ni	Mo	Mn	Si	P	S	Cu	—	—	—	—	—	—	Other		
18. STAINLESS STEELS, CAST — Austenitic (continued)																		
bal	.03	19.00	9.00	—	1.50	2.00	.04	.04	—								ASTM A451	Grade CPF3A
bal	.08	19.00	9.00	—	1.50	2.00	.04	.04	—								ASTM A296	Grade CF-8
bal	.08	19.00	9.00	—	1.50	2.00	.04	.04	—								ASTM A351	Grade CF-8
bal	.08	19.00	9.00	—	1.50	2.00	.04	.04	—								ASTM A351	Grade CF-8A
bal	.08	19.00	9.00	—	1.50	2.00	.04	.04	—								ASTM A451	Grade CPF8
bal	.08	19.00	9.00	—	1.50	1.00	.04	.04	—								ASTM A451	Grade CPF8A
bal	.08	19.00	9.00	—	2.00	.75	.04	.03	—								ASTM A452	Grade TP 304H
bal	.20	19.00	9.00	—	1.50	2.00	.04	.04	—								ASTM A296	Grade CF-20
bal	.08	19.00	10.00	—	1.50	2.00	.04	.04	—							Cb 8xC, 1.0 max.	ASTM A296	Grade CF-8C
bal	.08	19.00	10.00	—	1.50	2.00	.04	.04	—							Cb 8xC, 1.0 max.	ASTM A351	Grade CF-8C
bal	.08	19.00	10.00	—	2.00	.75	.04	.03	—							Cb + Ta 8xC, 1.0 max.	ASTM A452	Grade TP 347H
bal	.08	19.00	10.00	—	1.50	1.00	.04	.04	—							Cb 8xC, 1.0 max.	ASTM A451	Grade CPF8C
bal	.08	19.00	10.00	—	1.50	1.00	.04	.04	—							Ta .10 max.; Cb 8xC, 1.0 max.	ASTM A451	Grade CPF8C Ta max.
bal	.12	22.00	12.00	—	1.50	2.00	.04	.04	—								ASTM A296	Grade CG-12
bal	.08	25.00	12.00	—	1.50	1.50	.04	.04	—								ASTM A351	Grade CH-8
bal	.08	25.00	12.00	—	1.50	1.00	.04	.04	—								ASTM A451	Grade CPH8
bal	.10	25.00	12.00	—	1.50	2.00	.04	.04	—								ASTM A351	Grade CH-10
bal	.10	25.00	12.00	—	1.50	1.00	.04	.04	—								ASTM A451	Grade CPH10
bal	.20	25.00	12.00	—	1.50	1.00	.04	.04	—								ASTM A451	Grade CPH20
bal	.20	25.00	12.00	—	1.50	2.00	.04	.04	—								ASTM A296	Grade CH-20
bal	.20	25.00	12.00	—	1.50	2.00	.04	.04	—								ASTM A351	Grade CH-20
bal	.20	25.00	20.00	—	1.50	1.00	.04	.04	—								ASTM A451	Grade CPK20
bal	.20	25.00	20.00	—	1.50	1.75	.04	.04	—								ASTM A351	Grade CK-20
bal	.20	25.00	20.00	—	2.00	2.00	.04	.04	—								ASTM A296	Grade CK-20
bal	.30	25.00	20.00	—	1.50	1.75	.04	.04	—								ASTM A351	Grade HK-30
bal	.40	25.00	20.00	—	1.50	1.75	.04	.04	—								ASTM A351	Grade HK-40

COMPOSITION, %																	MATERIAL DESIGNATION	
Fe	C	Cr	Ni	Mo	Mn	Si	P	S	Cu	—	—	—	—	—	—	Other		
18. STAINLESS STEELS, CAST — Austenitic (continued)																		
bal	.30	15.00	35.00	.50	2.00	2.50	.04	.04	—								ASTM A351	Grade HT-30
bal	.60	15.00	35.00	.50	2.00	2.50	.04	.04	—								ASTM A297	Grade HT
bal	.10	17.00	13.00	3.00	2.00	.75	.04	.03	—								ASTM A452	Grade TP 316H
bal	.10	17.00	15.00	2.00	1.50	1.00	.04	.04	—							Cb 10xC, 1.2 max.	ASTM A451	Grade CPF10MC
bal	.10	17.00	15.00	2.00	1.50	1.50	.04	.04	—							Cb 10xC, 1.2 max.	ASTM A351	Grade CF-10MC
bal	.50	17.00	35.00	.50	1.50	2.00	.04	.04	—								ASTM A608	Grade HT50
bal	.03	19.00	10.00	3.00	1.50	1.50	.04	.04	—								ASTM A296	Grade CF-3M
bal	.03	19.00	10.00	3.00	1.50	1.50	.04	.04	—								ASTM A351	Grade CF-3M
bal	.03	19.00	10.00	3.00	1.50	1.50	.04	.04	—								ASTM A351	Grade CF-3MA
bal	.07	19.00	24.00	3.00	1.00	3.00	.04	.03	2.00								ASTM A451	Grade CPF3M
bal	.08	19.00	10.00	3.00	1.50	2.00	.04	.04	—								ASTM A296	Grade CN-7MS
bal	.08	19.00	10.00	3.00	1.50	1.50	.04	.04	—								ASTM A296	Grade CF-8M
bal	.08	19.00	10.00	3.00	1.50	1.00	.04	.04	—								ASTM A351	Grade CF-8M
bal	.08	19.00	11.00	4.00	1.50	1.50	.04	.04	—								ASTM A451	Grade CPF8M
bal	.16	19.00	9.00	.80	1.50	2.00	.04	.04	—								ASTM A296	Grade CG-8M
bal	.30	19.00	9.00	.50	1.50	2.00	.04	.04	—								ASTM A296	Grade CF-16F
bal	.30	19.00	9.00	.50	2.00	2.00	.04	.04	—								ASTM A608	Grade HF30
bal	.50	19.00	39.00	.50	1.50	2.00	.04	.04	—								ASTM A297	Grade HF
bal	.60	19.00	39.00	.50	2.00	2.50	.04	.04	—								ASTM A608	Grade HU50
bal	.07	20.00	29.00	3.00	1.50	1.50	.04	.04	—								ASTM A297	Grade HU
bal	.07	20.00	29.00	3.00	1.50	1.50	.04	.04	3.00								ASTM A351	Grade CN-7M
bal	.40	20.00	25.00	.50	1.50	2.00	.04	.04	—								ASTM A296	Grade CN-7M
bal	.40	20.00	25.00	.50	2.00	2.00	.04	.04	—								ASTM A608	Grade HN40
bal	.30	25.00	12.00	.50	1.50	2.00	.04	.04	—								ASTM A297	Grade HN
bal	.30	25.00	20.00	.50	1.50	2.00	.04	.04	—								ASTM A608	Grade HH30
bal	.33	25.00	12.00	.50	1.50	2.00	.04	.04	—								ASTM A608	Grade HK30
bal	.40	25.00	20.00	.50	1.50	2.00	.04	.04	—								ASTM A608	Grade HH33
																	ASTM A608	Grade HK40

COMPOSITION, %																	MATERIAL DESIGNATION
Fe	C	Cr	Ni	Mo	Mn	Si	P	S	Cu	—	—	—	—	—	—	Other	
18. STAINLESS STEELS, CAST — Austenitic (continued)																	
bal	.50	25.00	12.00	.50	2.00	2.00	.04	.04	—								ASTM A297 Grade HH
bal	.50	25.00	20.00	.50	2.00	2.00	.04	.04	—								ASTM A297 Grade HK
bal	.60	26.00	35.00	.50	2.00	2.50	.04	.04	—								ASTM A297 Grade HP
bal	.40	28.00	15.00	.50	2.00	2.00	.04	.04	—								ASTM A297 Grade HI
bal	.40	28.00	15.00	.50	1.50	2.00	.04	.04	—								ASTM A608 Grade HI35
bal	.50	28.00	5.00	.50	1.50	2.00	.04	.04	—								ASTM A297 Grade HD
bal	.50	28.00	5.00	.50	1.50	2.00	.04	.04	—								ASTM A608 Grade HD50
bal	.30	29.00	20.00	.50	1.50	2.00	.04	.04	—								ASTM A608 Grade HL30
bal	.40	29.00	9.00	.50	1.50	2.00	.04	.04	—								ASTM A608 Grade HE35
bal	.40	29.00	9.00	.50	2.00	2.00	.04	.04	—								ASTM A297 Grade HE
bal	.40	29.00	20.00	.50	1.50	2.00	.04	.04	—								ASTM A608 Grade HL40
bal	.50	29.00	20.00	.50	2.00	2.00	.04	.04	—								ASTM A297 Grade HL
18. STAINLESS STEELS, CAST — Martensitic																	
bal	.15	7.00	—	.60	.50	1.00	.03	.03	—								ASTM A426 Grade CP7
bal	.20	9.00	—	1.00	.50	1.00	.03	.03	—								ASTM A426 Grade CP9
bal	.15	12.00	—	.50	1.00	1.50	.04	.04	—								ASTM A426 Grade CPCA15
bal	.15	12.00	1.00	.50	1.00	1.50	.04	.04	—								ASTM A217 Grade CA-15
bal	.15	12.00	1.00	50	1.00	1.50	.04	.04	—								ASTM A296 Grade CA-15
bal	.15	12.00	1.00	.50	1.00	1.50	.04	.04	—								ASTM A487 Class CA15n
bal	.15	12.00	1.00	1.00	1.00	.65	.04	.04	—								ASTM A296 Grade CA15M
bal	.15	12.00	1.00	1.00	1.00	.65	.04	.04	—							.03V	ASTM A487 Class CA15M
bal	.40	12.00	1.00	.50	1.00	1.50	.04	.04	—								ASTM A296 Grade CA-40
19. PRECIPITATION HARDENING STAINLESS STEELS, CAST																	
bal	.10	16.00	4.00	3.00	1.00	.50	—	—	—							.10N	AM-355
bal	.07	17.00	4.00	—	1.00	1.00	—	—	2.50								ACI Grade CB-7Cu
bal	.07	17.00	4.00	—	1.00	1.00	—	—	2.50								17-4 PH
bal	.04	25.00	5.00	2.00	1.00	1.00	—	—	3.00								ACI Grade CD-4MCu
bal	.04	25.00	5.00	2.00	1.00	1.00	.04	.04	3.00								ASTM A351 Grade CD-4MCu

COMPOSITION, %																	
Fe	C	Mn	Cr	Ni	Mo	Si	P	—	—	—	—	—	—	—	—	Other	MATERIAL DESIGNATION
20. AUSTENITIC MANGANESE STEELS, CAST																	
bal	1.30	8.00	—	—	1.00	1.00	.07										
bal	1.25	11.00	—	—	—	1.00	.07										ASTM A128 Grade F
bal	1.00	14.00	—	—	—	1.00	.07										ASTM A128 Grade A
bal	1.15	14.00	—	—	—	1.00	07										ASTM A128 Grade B-1
bal	1.25	14.00	—	—	—	1.00	07										ASTM A128 Grade B-2
bal	1.30	14.00	—	—	—	1.00	.07										ASTM A128 Grade B-3
bal	1.20	14.00	2.00	—	—	1.00	.07										ASTM A128 Grade B-4
bal	1.20	14.00	—	3.50	—	1.00	.07										ASTM A128 Grade C
bal	1.20	14.00	—	—	1.20	1.00	07										ASTM A128 Grade D
bal	1.40	14.00	—	—	2.00	1.00	07										ASTM A128 Grade E-1
																	ASTM A128 Grade E-2

COMPOSITION, %																	
Fe	C	Si	Mn	Cr	Ni	Cu	P	S	Mo	—	—	—	—	—	—	Other	MATERIAL DESIGNATION
21. GRAY CAST IRONS — Ferritic																	
bal	3.50	2.40	—	—	—	—	—	—	—								
bal	3.50	2.60	.80	—	—	—	.25	.15	—								ASTM A48 Class 20
21. GRAY CAST IRONS — Pearlitic-Ferritic																	SAE J431c Grade G1800
bal	3.30	2.20	—	—	—	—	—	—	—								
bal	3.30	2.20	.90	—	—	—	.20	.15	—								ASTM A48 Class 25
21. GRAY CAST IRONS — Pearlitic																	SAE J431c Grade G2500
bal	3.00	1.90	.60	—	—	—	.20	.06	—								
bal	3.10	2.00	—	—	—	—	—	—	—								ASTM A48 Class 40
bal	3.20	2.20	.50	—	—	—	.20	.06	—								ASTM A48 Class 35
bal	3.30	2.10	.90	—	—	—	.15	.15	—								ASTM A48 Class 30
																	SAE J431c Grade G3000

COMPOSITION, %																	MATERIAL DESIGNATION
Fe	C	Si	Mn	Cr	Ni	Cu	P	S	Mo	—	—	—	—	—	—	Other	
21. GRAY CAST IRONS — Pearlitic plus Free Carbides																	
bal	3.15	2.00	—	--	—	—	.20	.10	—								ASTM A48 Class 45
bal	3.15	2.00	—	—	—	—	.20	.10	—								ASTM A48 Class 50
bal	3.15	2.20	.90	—	—	—	.12	.15	—								SAE J431c Grade G3500
bal	3.15	2.00	1.00	—	—	—	.10	.15	—								SAE J431c Grade G4000
21. GRAY CAST IRONS — Pearlitic or Acicular plus Free Carbides																	
bal	3.50	1.80	.90	—	—	—	.20	.06	—								ASTM A48 Class 55
bal	3.50	1.80	—	—	--	—	.20	06	—								ASTM A48 Class 60
21. GRAY CAST IRONS — Austenitic (NI-RESIST)																	
bal	2.40	1.50	1.00	.10	35.00	.50	—	.12	—								ASTM A436 Type 5
bal	2.60	1.50	1.00	3.00	30.00	.50	—	.12	—								ASTM A436 Type 3
bal	2.60	5.50	1.00	5.00	31.00	.50	—	.12	—								ASTM A436 Type 4
bal	3.00	2.50	1.00	2.00	16.00	6.50	—	.12	—								ASTM A436 Type 1
bal	3.00	2.50	1.00	3.00	16.00	6.50	—	.12	—								ASTM A436 Type 1b
bal	3.00	2.50	1.00	2.00	20.00	.50	—	.12	—								ASTM A436 Type 2
bal	3.00	2.50	1.00	4.00	20.00	.50	—	.12	—								ASTM A436 Type 2b
bal	3.00	2.00	1.00	1.50	20.00	4 50	—	.12	1.00								ASTM A436 Type 6
23. DUCTILE CAST IRONS — Ferritic																	
bal	3.50	2.50	.60	—	—	—	10	.03	—								SAE J434c Grade D4018
bal	3.50	2.50	.60	—	—	—	.10	.03	—								SAE J434c Grade D4512
bal	3.60	2.30	.60	—	--	—	.08	.03	—								ASTM A536 Grade 60-40-18
bal	3.60	2.30	.60	—	—	—	.08	.03	—								ASTM A536 Grade 65-45-12
23. DUCTILE CAST IRONS — Ferritic-Pearlitic																	
bal	3.50	2.50	.60	—	—	—	.10	.03	—								SAE J434c Grade D5506
bal	3.60	2.30	.60	—	—	—	.08	.03	—								ASTM A536 Grade 80-55-06
23. DUCTILE CAST IRONS — Pearlitic-Martensitic																	
bal	3.50	2.50	.60	—	—	—	.10	.03	—								SAE J434c Grade D7003
bal	3.60	2.30	.60	—	—	—	.10	.03	—								ASTM A536 Grade 100-70-03

COMPOSITION, %																	MATERIAL DESIGNATION
Fe	C	Si	Mn	Cr	Ni	Cu	P	S	Mo	—	—	—	—	—	—	Other	
22. DUCTILE CAST IRONS — Martensitic																	
bal	3.50	2.50	.60	—	—	—	.10	.03	—								SAE J434c Grade DQ&T
bal	3.60	2.30	.60	—	—	—	10	.03	—								ASTM A536 Grade 120-90-02
23. DUCTILE CAST IRONS — Austenitic (NI-RESIST Ductile)																	
bal	2 40	2.80	1 00	.10	36.00	—	.08	—	—								ASTM A439 Type D-5
bal	2.40	2.80	1.00	3.00	36.00	—	.08	—	—								ASTM A439 Type D-5B
bal	2.60	2.80	1.00	1.50	32.00	—	.08	—	—								ASTM A439 Type D-3A
bal	2.60	2.80	1.00	3.00	32.00	—	08	—	—								ASTM A439 Type D-3
bal	2.60	6 00	1.00	5.00	32.00	—	.08	—	—								ASTM A439 Type D-4
bal	2.70	2.00	4.00	.20	24.00	—	.08	—	—								ASTM A571 Type D-2M
bal	2.90	3.00	2.20	.50	24.00	—	08	—	—								ASTM A439 Type D-2C
bal	3.00	3.00	1.00	2.50	22.00	—	.08	—	—								ASTM A439 Type D-2
bal	3.00	3.00	1.00	3.50	22 00	—	08	—	—								ASTM A439 Type D-2B
24. MALLEABLE CAST IRONS — Ferritic																	
bal	2.20	1.15	.35	—	—	—	.16	.08	—								ASTM A47 Grade 35018
bal	2.50	1.30	.40	—	—	—	.02	.16	—								ASTM A47 Grade 32510
bal	2.50	1.50	1.00	—	—	—	.10	.15	—								ASTM A602 Grade M3210
bal	2.50	1.50	1.00	—	—	—	.10	15	—								SAE J158 Grade M3210
24. MALLEABLE CAST IRONS — Pearlitic																	
bal	2.20	1.15	.60	—	—	—	.10	.08	—								ASTM A220 Grade 40010
bal	2.20	1.15	.60	—	—	—	.10	.08	—								ASTM A220 Grade 45006
bal	2.20	1.15	.70	—	—	—	.10	.08	—								ASTM A220 Grade 45008
bal	2.20	1.20	.80	—	—	—	.08	.10	—								ASTM A220 Grade 50005
bal	2.20	1.30	.60	—	—	—	.08	.10	—								ASTM A602 Grade M4504
bal	2.20	1.30	.60	—	—	—	.08	10	—								SAE J158 Grade M4504
bal	2.20	1.30	.80	—	—	—	08	.10	—								SAE J158 Grade M5003

COMPOSITION, %																	MATERIAL DESIGNATION
Fe	C	Si	Mn	Cr	Ni	Cu	P	S	Mo	—	—	—	—	—	—	Other	
24. MALLEABLE CAST IRONS — Tempered Martensite																	
bal	2.20	1.10	.80	—	—	—	.10	.10	—								ASTM A220 Grade 80002
bal	2.20	1.30	.80	—	—	—	.08	.10	—								ASTM A602 Grade M5503
bal	2.20	1.30	.80	—	—	—	.08	.10	—								SAE J158 Grade M5503
bal	2.30	1.20	.50	—	—	—	.08	.10	—								ASTM A220 Grade 60004
bal	2.30	1.30	1.00	—	—	—	.08	.10	—								ASTM A602 Grade M7002
bal	2.30	1.30	1.00	—	—	—	.08	.10	—								SAE J158 Grade M7002
bal	2.30	1.30	1.00	—	—	—	.08	.10	—								ASTM A220 Grade 70003
bal	2.30	1.30	1.00	—	—	—	.10	.10	—								ASTM A602 Grade M8501
bal	2.30	1.30	1.00	—	—	—	.10	.10	—								SAE J158 Grade M8501
bal	2.30	1.30	1.00	—	—	—	.10	.10	—								ASTM A220 Grade 90001
25. WHITE CAST IRONS (ABRASION RESISTANT)																	
bal	2.30	1.00	1.00	21.00	1.50	1.20	.10	.06	1.50								ASTM A532 Class II, Type D
bal	2.60	1.00	1.00	13.00	.50	1.20	.10	.06	.75								ASTM A532 Class II, Type A
bal	2.60	1.00	1.00	16.00	.50	1.20	.10	.06	2.00								ASTM A532 Class II, Type B
bal	2.70	1.00	1.00	25.00	1.50	1.20	.10	.06	1.50								ASTM A532 Class III, Type A
bal	2.75	.80	1.30	3.00	4.00	—	.30	15	1.00								ASTM A532 Class I, Type B
bal	3.00	1.00	1.00	21.00	1.50	1.20	.10	.06	1.50								ASTM A532 Class II, Type E
bal	3.00	1.75	1.30	9.00	6.00	—	.10	15	1.00								ASTM A532 Class I, Type D
bal	3.20	1.00	1.00	16.00	.50	1.20	.10	.06	3.00								ASTM A532 Class II, Type C
bal	3.30	.80	1.30	3.00	4.00	—	.30	.15	1.00								ASTM A532 Class I, Type A
bal	3.50	.80	1.30	1.30	3.50	—	.30	.15	1.00								ASTM A532 Class I, Type C
26. HIGH SILICON CAST IRONS																	
bal	.85	14.50	.50	—	—	—	.07	.08	—								Duriron
bal	.85	14.50	.65	—	—	—	—	—	3.00								Duriclor
bal	1.00	14.50	1.50	.50	—	.50	—	—	.50								ASTM A518

COMPOSITION, %																	MATERIAL DESIGNATION
Ni	Cr	C	Si	Mn	Al	Ti	Fe	N	P	S	—	—	—	—	—	Other	
27. CHROMIUM-NICKEL ALLOY CASTINGS																	
bal	50.00	.10	1.00	.30	.25	.50	1.00	.30	.02	.02							ASTM A560 Grade 50Cr-50Ni
bal	60.00	.10	1.00	.30	.25	.50	1.00	.30	.02	.02							ASTM A560 Grade 60Cr-40Ni

COMPOSITION, %																	MATERIAL DESIGNATION
Al	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Sn	—	—	—	—	—	Other	
28. ALUMINUM ALLOYS, WROUGHT																	
99.45	—	—	—	—	—	—	—	—	—	—							EC
99.60	—	.25	—	.03	.03	—	—	.05	.03	—							1060
99.75	.15	*	.10	.02	.02	—	—	.04	.02	—							1175
99.45	.55	*	.05	.05	.05	—	—	.05	.03	—							1145
99.35	.65	*	.05	.05	.05	—	—	.10	.06	—							1235
99.00	1.00	*	.12	.05	—	—	—	.10	—	—							1100
bal	.08	.10	.10	.03	1.00	—	—	.05	—	—							5657
bal	.08	.10	.10	.10	2.80	—	—	.05	—	—							5252
bal	.08	.10	.20	.45	1.20	—	—	.05	—	—							5457
bal	.12	.15	2.30	.10	2.30	.04	—	6.50	.06	—							7050
bal	.15	.20	1.60	.10	2.50	.25	—	5.60	.10	—							7175
bal	.20	.30	6.30	.30	—	—	—	—	—	—							2021
bal	.20	.30	6.80	.40	.02	—	—	.10	.10	—							2219
bal	.25	.35	.05	.50	1.50	.05	—	4.00	.05	—						.15Zr	7004
bal	.25	.35	1.60	.20	2.50	.15	—	7.70	.10	—							7049
bal	.25	.40	.10	.10	2.80	.35	—	.10	—	—							5052
bal	.25	.40	.10	1.00	3.00	.20	—	.25	.20	—							5454
bal	.25	.40	.10	.10	3.90	.35	—	.20	.20	—							5154
bal	.25	.40	.10	1.00	5.50	.20	—	.25	.20	—							5456
bal	.25	1.30	2.70	—	1.80	—	1.00	.10	.10	—							2618

*Included with silicon.

COMPOSITION, %																	MATERIAL DESIGNATION
Al	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Sn	—	—	—	—	—	Other	
28. ALUMINUM ALLOYS, WROUGHT (continued)																	
bal	.30	.40	.10	.20	2.80	.20	—	4.00	—	—							7039
bal	.30	.40	.10	.20	5.00	.20	—	.10	—	—							5056
bal	.30	.40	.60	.20	3.30	.20	—	4.30	—	—							7079
bal	.30	.70	.20	.20	1.00	.10	—	.25	—	—							5005
bal	.30	.70	.25	1.50	1.30	—	—	.25	—	—							3004
bal	.35	.40	.10	.70	1.80	.20	—	5.00	.06	—						.14Zr	7005
bal	.35	.40	2.60	.20	3.40	.35	—	8.00	.20	—							7001
bal	.40	*	.04	.01	2.80	.35	—	.10	—	—							5652
bal	.40	.40	.10	1.00	4.90	.25	—	.25	.15	—							5083
bal	.40	.50	.10	.70	4.50	.25	—	.25	.15	—							5086
bal	.40	.50	2.00	.30	2.90	.25	—	6.00	.20	—							7075
bal	.40	.50	2.40	.30	3.10	.35	—	7.00	.20	—							7178
bal	.40	.70	.20	.10	1.80	.10	—	.25	--	—							5050
bal	.40	.70	6.00	—	—	—	—	.30	—	—							2011
bal	.45	*	.05	.01	3.90	.35	—	.20	.05	—							5254
bal	.50	.50	4.90	.90	1.50	.10	—	.25	.15	—							2024
bal	.50	.80	.40	.10	.80	—	—	.20	—	—							6951
bal	.55	.35	.10	—	1.40	.35	—	.10	—	—							6053
bal	.60	.15	.20	.05	.90	—	—	—	—	—							6463
bal	.60	.35	.10	.10	.90	.10	—	.10	.10	—							6063
bal	.60	.70	.20	1.50	—	—	—	.10	—	—							3003
bal	.60	.70	.30	1.50	.60	.10	--	.25	.10	—							3005
bal	.65	.50	.10	—	1.50	.35	—	2.40	—	—							6253
bal	.70	.50	.10	.03	.80	.03	—	.10	—	—							6101
bal	.80	.70	.40	.15	1.20	.15	—	.25	.15	—							6262
bal	.80	.70	.40	.15	1.20	.35	—	.25	.15	—							6061
bal	.80	.70	3.00	.20	.50	.10	—	.25	—	—							2117

*included with silicon.

COMPOSITION, %																	
Al	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Sn	—	—	—	—	—	Other	MATERIAL DESIGNATION
28. ALUMINUM ALLOYS, WROUGHT (continued)																	
bal	.80	.70	4.50	.80	.80	.10	—	.25	.15	—							2017
bal	.90	1.00	4.50	.20	.90	.10	2.00	.25	—	—							2018
bal	.90	1.00	4.50	.20	1.80	.10	2.00	.25	—	—							2218
bal	1.00	.70	5.00	1.00	.80	.10	—	.25	.15	—							2014
bal	1.00	1.00	5.00	.80	.05	.10	—	.25	.15	—							2025
bal	1.20	1.00	.35	.20	.80	.35	—	.25	.15	—							6151
bal	1.70	.50	.40	1.00	1.20	.10	—	.25	.15	—							6070
bal	1.80	.50	1.20	1.10	1.40	.40	—	.25	.20	—							6066
bal	13.50	1.00	1.30	—	1.30	.10	1.30	.25	—	—							4032
29. ALUMINUM ALLOYS, CAST — Sand and Permanent Mold																	
bal	—	—	8.00	.50	6.00	—	.50	—	—	—							A140
bal	.06	.10	5.00	.35	—	—	—	—	.35	—						.15V, .25Zr	224.0
bal	.10	.15	4.60	.35	.35	—	—	—	.25	—							201.0
bal	.15	.15	.05	.25	7.00	—	—	—	.25	—							535.0
bal	.15	.15	.10	.10	1.00	.20	—	7.00	.20	—							771.0
bal	.15	.50	.65	.05	.80	—	—	7.00	.25	—							A712.0
bal	.20	.80	.20	.60	1.80	.40	—	3.00	.25	—							705.0
bal	.20	.80	.20	.60	2.40	.40	—	4.50	.25	—							707.0
bal	.20	1.50	5.00	.25	—	—	1.50	—	.20	—						.20Zr,.25Sb,.25Co	Hiduminium RR-350
bal	.25	.30	.25	.15	10.00	—	—	.15	.25	—							520.0
bal	.25	1.10	1.00	.60	.50	.35	.15	8.00	.25	—							713.0
bal	.30	.40	.10	.30	4.00	—	—	2.00	.20	—							A514.0
bal	.30	.50	.25	.10	.65	.60	—	6.00	.20	—							D712.0
bal	.35	.50	.15	.35	4.00	—	—	15	.25	—							514.0
bal	.40	.70	2.00	.10	.90	—	1.50	—	.20	7.00							B850.0

COMPOSITION, %																	MATERIAL DESIGNATION
Al	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Sn	—	—	—	—	—	Other	
28. ALUMINUM ALLOYS, CAST — Sand and Permanent Mold (continued)																	
bal	.70	.70	1.00	.10	.10	—	1.00	—	.20	7.00							850.0
bal	.70	1.00	4.50	.35	1.80	.25	2.30	.35	.25	—							242.0
bal	1.50	1.00	5.00	.35	.03	—	—	.35	.25	—							295.0
bal	2.00	.60	.35	.80	4.00	.25	—	.35	.25	—							B514.0
bal	2.00	1.50	10.00	.50	.35	—	.50	.80	.25	—							222.0
bal	2.50	.70	1.00	.10	.10	—	.70	—	.20	7.00							A850.0
bal	3.00	1.20	5.00	.35	.05	—	.35	.50	.25	—							B295.0
bal	3.00	1.20	8.00	.60	.10	—	.35	2.50	.25	—							213.0
bal	3.50	1.20	4.00	.50	.10	—	.35	1.00	.25	—							208.0
bal	5.50	.20	1.25	.10	.60	—	—	.10	.20	—							C355.0
bal	5.50	.60	1.25	.50	.60	.20	—	.35	.25	—							355.0
bal	6.00	.80	.15	.35	.05	—	—	.35	.25	—							B443.0
bal	6.00	1.00	5.00	.50	.10	—	—	1.00	.25	—							308.0
bal	6.50	1.00	4.00	.50	.10	—	.35	1.00	.25	—							319.0
bal	7.50	.15	.05	.03	.60	—	—	.05	.20	—							357 0
bal	7.50	.20	.20	.10	.40	—	—	.10	.20	—							A356 0
bal	7.50	.60	.25	.35	.40	—	—	.35	.25	—							356.0
bal	8.50	1.00	2.00	.60	.60	.35	.25	1.50	.25	—							328 0
bal	9.00	.20	.20	.10	.60	—	—	.10	.20	—							359.0
bal	9.00	.20	1.80	.10	.50	—	—	.10	.20	—							354 0
bal	10.00	1.00	4.00	.50	.50	—	.50	1.00	.25	—							333.0
bal	10.50	1.20	4.00	.50	1.00	—	.50	1.00	.25	—							F332.0
bal	13.00	1.20	1.50	.35	1.00	—	2.50	.35	.25	—							A332.0

COMPOSITION, %																	
Al	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Sn	—	—	—	—	—	Other	MATERIAL DESIGNATION
29. ALUMINUM ALLOYS, CAST — Die Castings																	
bal	.35	1.80	.25	.35	8.00	—	.15	.15	—	.15							518.0
bal	5.50	2.00	.60	.35	.10	—	.50	.50	—	.15							C443.0
bal	8.50	1.30	3.50	.50	.10	—	.50	3.00	—	.35							A380.0
bal	8.50	2.00	3.50	.50	.10	—	.50	3.00	—	.35							380.0
bal	9.50	1.30	.60	.35	.50	—	.50	.50	—	.15							A360.0
bal	9.50	2.00	.60	.35	.50	—	.50	.50	—	.15							360.0
bal	10.50	1.30	2.50	.50	.10	—	.30	3.00	—	.15							383.0
bal	11.50	1.30	4.00	.50	.10	—	.50	1.00	—	.35							A384.0
bal	12.00	1.30	1.00	.35	.10	—	.50	.50	—	.15							A413.0
bal	12.00	2.00	1.00	.35	.10	—	.50	.50	—	.15							413.0
bal	17.00	1.00	4.50	.10	.60	—	—	.10	.20	—							390.0
bal	19.00	1.50	.60	.50	1.00	—	.50	.50	.20	.30							392.0

COMPOSITION, %																	
Mg	Al	Mn	Zn	Zr	Cu	Ni	Si	Fe	—	—	—	—	—	—	—	Other	MATERIAL DESIGNATION
30. MAGNESIUM ALLOYS, WROUGHT																	
bal	—	—	.30	.70	.10	.01	—	—									
bal	—	.80	—	—	—	—	—	—								3.20Th	HK31A
bal	—	1.20	—	—	—	—	—	—								2.00Th	HM21A
bal	—	—	4.00	.45	.10	.01	—	—								3.00Th	HM31A
bal	—	—	5.50	.45	—	—	—	—									ZK40A
bal	2.00	.15	1.20	—	.05	.002	.05	.005									ZK60A
bal	3.00	.20	1.00	—	—	—	—	—								.20Ca	AZ21A
bal	3.00	.15	1.00	—	.10	.03	.10	—								.04Ca	AZ31B
bal	6.50	.15	1.00	—	.05	.005	.10	.005									AZ31C
bal	8.50	.12	.50	—	.05	.005	.10	.005									AZ61A
																	AZ80A

COMPOSITION, %																	
Mg	Al	Mn	Zn	Zr	Cu	Ni	Si	Fe	—	—	—	—	—	—	—	Other	MATERIAL DESIGNATION
31. MAGNESIUM ALLOYS, CAST																	
bal	—	—	2.60	.70	.10	.01	—	—								3.20 Rare Earths	EZ33A
bal	—	—	.30	.70	.10	.01	—	—								3.20Th	HK31A
bal	—	—	2.10	.70	.10	.01	—	—								3.20Th	HZ32A
bal	—	—	—	.60	—	—	—	—									K1A
bal	—	—	—	.70	.10	.01	—	—								2.20 Rare Earths, 2.50 Ag	QE22A
bal	—	.15	4.20	.70	.10	.01	—	—								1.20 Rare Earths	ZE41A
bal	—	—	5.70	.70	—	—	—	—								2.50 Rare Earths	ZE63A
bal	—	—	5.70	.70	.10	.01	—	—								1.80Th	ZH62A
bal	—	—	4.60	.70	.10	.01	—	—									ZK51A
bal	—	—	6.00	.60	—	—	—	—									ZK61A
bal	4.20	.35	.12	—	.06	.03	1.00	—									AS41A
bal	6.00	.13	.20	—	.35	.03	.50	—									AM60A
bal	6.00	.15	3.00	—	.15	.01	.25	—									AZ63A
bal	7.60	.13	.70	—	.10	.01	.30	—									AZ81A
bal	8.70	.13	.70	—	.10	.01	.30	—									AZ91C
bal	9.00	.10	2.00	—	.25	.01	.30	—									AZ92A
bal	9.00	.13	.70	—	.10	—	.50	—								.03Mo	AZ91A
bal	9.00	.15	.70	—	.25	.01	.20	—									AZ91B
bal	10.00	.10	.30	—	.10	.01	.30	—									AM100A

COMPOSITION, %																	
Ti	Al	Sn	Zr	Mo	V	Cr	Fe	Si	Pd	O	—	—	—	—	—	Other	MATERIAL DESIGNATION
32. TITANIUM ALLOYS, WROUGHT																	
99.5	—	—	—	—	—	—	—	—	—	—							Ti 99.5
99.2	—	—	—	—	—	—	—	—	—	—							Ti 99.2

COMPOSITION, %																	
Ti	Al	Sn	Zr	Mo	V	Cr	Fe	Si	Pd	O	—	—	—	—	—	Other	MATERIAL DESIGNATION
32. TITANIUM ALLOYS, WROUGHT (continued)																	
99.0	—	—	—	—	—	—	—	—	—	—							Ti 99.0
bal	—	—	—	—	—	—	—	—	.20	—							Ti-0.2 Pd
98.9	—	—	—	—	—	—	—	—	—	—							Ti 98.9
bal	--	—	—	.30	—	—	.30	—	—	—						.80 Ni	Ti CODE-12
bal	—	—	—	—	—	—	—	—	—	—						8.00 Mn	Ti-8 Mn
bal	1.00	—	—	—	8.00	—	5.00	—	—	—							Ti-1Al-8V-5Fe
bal	2.50	11.00	5.00	1.00	—	—	.10	.25	—	—							Ti-2Al-11Sn-5Zr-1Mo
bal	3.00	—	4.00	4.00	8.00	6.00	.30	—	—	—							Ti-3Al-8V-6Cr-4Mo-4Zr
bal	3.00	—	—	—	2.50	—	—	—	—	—							Ti-3Al-2.5V
bal	3.00	—	—	8.00	8.00	—	2.00	—	—	—							Ti-8Mo-8V-2Fe-3Al
bal	3.00	—	—	—	10.00	—	2.00	—	—	—							Ti-10V-2Fe-3Al
bal	3.00	-	—	—	13.00	11.00	.35	—	—	—							Ti-13V-11Cr-3Al
bal	5.00	2.50	—	—	—	—	—	—	—	—							Ti-5Al-2.5Sn
bal	5.00	2.50	—	--	—	—	—	—	—	—						Extra Low Interstitials	Ti-5Al-2.5Sn ELI
bal	5.00	6.00	2.00	1.00	—	—	—	—	—	—							Ti-5Al-6Sn-2Zr-1Mo
bal	5.00	2.00	2.00	4.00	—	4.00	.30	—	—	—							Ti-5Al-2Sn-2Zr-4Mo-4Cr
bal	5.00	2.00	2.00	4.00	—	4.00	.30	—	—	—							Ti-17
bal	6.00	—	—	.80	—	—	.20	—	—	—						2.00Cb 1.00Ta	Ti-6Al-2Cb-1Ta-0.8Mo
bal	6.00	2.00	4.00	2.00	—	—	.25	—	—	—							Ti-6Al-2Sn-4Zr-2Mo
bal	6.00	2.00	4.00	2.00	—	—	—	.25	—	—							Ti-6Al-2Sn-4Zr-2Mo-.25Si
bal	6.00	2.00	4.00	6.00	—	—	.15	—	—	—							Ti-6Al-2Sn-4Zr-6Mo
bal	6.00	—	—	—	4.00	—	.30	—	—	—							Ti-6Al-4V
bal	6.00	—	—	—	4.00	—	—	—	—	—						Extra Low Interstitials	Ti-6Al-4V ELI
bal	6.00	2.00	—	—	6.00	—	.70	—	—	—						.70Cu	Ti-6Al-6V-2Sn
bal	7.00	—	—	4.00	—	—	.30	—	—	—							Ti-7Al-4Mo
bal	8.00	—	—	1.00	1.00	—	.30	—	—	—							Ti-8Al-1Mo-1V
bal	--	4.50	6.00	11.50	—	—	.35	—	—	—							Ti-11.5Mo-6Zr-4.5Sn

COMPOSITION, %																	
Ti	Al	Sn	Zr	Mo	V	Cr	Fe	Si	Pd	O	—	—	—	—	—	Other	MATERIAL DESIGNATION
33. TITANIUM ALLOYS, CAST																	
99.0	—	—	—	—	—	—	—	—	—	—							TI 99.0
bal	—	—	—	—	—	—	—	—	.20	—							Ti-0.2Pd
bal	—	—	—	—	—	—	.20	—	—	.18							ASTM B367 Grade C-1
bal	—	—	—	—	—	—	.30	—	—	.25							ASTM B367 Grade C-2
bal	—	—	—	—	—	—	.20	—	.12	.18							ASTM B367 Grade C-7A
bal	—	—	—	—	—	—	.30	—	.12	.25							ASTM B367 Grade C-7B
bal	—	—	—	—	—	—	.30	—	—	.35							ASTM B367 Grade C-3
bal	—	—	—	—	—	—	.50	—	—	.40							ASTM B367 Grade C-4
bal	—	—	—	—	—	—	.30	—	.12	.35							ASTM B367 Grade C-8A
bal	—	—	—	—	—	—	.50	—	.12	.40							ASTM B367 Grade C-8B
bal	5.00	2.50	—	—	—	—	—	—	—	—							Ti-5Al-2.5Sn
bal	5.00	2.50	—	—	—	—	.50	—	—	.20							ASTM B367 Grade C-6
bal	6.00	—	—	—	4.00	—	.30	—	—	.20							Ti-6Al-4V
bal	6.00	—	—	—	4.00	—	.50	—	—	.20							ASTM B367 Grade C-5
bal	6.00	2.00	4.00	2.00	—	—	—	—	—	—							Ti-6Al-2Sn-4Zr-2Mo
bal	8.00	—	—	1.00	1.00	—	—	—	—	—							Ti-8Al-1Mo-1V

COMPOSITION, %																	
Cu	Ag	As	Sb	P	Te	Fe	Sn	Zn	Pb	Al	Si	Mn	Ni	Co	Cr	Other	MATERIAL DESIGNATION
34. COPPER ALLOYS, WROUGHT																	
99.99	—	—	—	.003	.001	—	—	—	—	—	—	—	—	—	—		101
99.95	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		102
99.95	.03	—	—	—	—	—	—	—	—	—	—	—	—	—	—		104
99.95	.03	—	—	—	—	—	—	—	—	—	—	—	—	—	—		105
99.95	.08	—	—	—	—	—	—	—	—	—	—	—	—	—	—		107
99.90	.04	—	—	—	—	—	—	—	—	—	—	—	—	—	—		109
99.90	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		110
																	111

COMPOSITION, %																	
Cu	Ag	As	Sb	P	Te	Fe	Sn	Zn	Pb	Al	Si	Mn	Ni	Co	Cr	Other	MATERIAL DESIGNATION
34. COPPER ALLOYS, WROUGHT (continued)																	
99.90	.03	—	—	—	—	—	—	—	—	—	—	—	—	—	—		113
99.90	.03	—	—	—	—	—	—	—	—	—	—	—	—	—	—		114
99.90	.05	—	—	—	—	—	—	—	—	—	—	—	—	—	—		115
99.90	.08	—	—	—	—	—	—	—	—	—	—	—	—	—	—		116
99.93	—	—	—	.01	—	—	—	—	—	—	—	—	—	—	—		119
99.90	—	—	—	.01	—	—	—	—	—	—	—	—	—	—	—		120
99.90	.01	—	—	.01	—	—	—	—	—	—	—	—	—	—	—		121
99.90	—	—	—	.02	—	—	—	—	—	—	—	—	—	—	—		122
99.88	—	.01	.003	—	.02	—	—	—	.004	—	—	—	.05	—	—	.003Bi	125
99.88	.03	.01	.003	—	.02	—	—	—	.004	—	—	—	.05	—	—	.003Bi	127
99.88	.03	.01	.003	—	.02	—	—	—	.004	—	—	—	.05	—	—	.003Bi	128
99.88	.05	.01	.003	—	.02	—	—	—	.004	—	—	—	.05	—	—	.003Bi	129
99.88	.08	.01	.003	—	.02	—	—	—	.004	—	—	—	.05	—	—	.003Bi	130
99.60	—	.30	—	.02	—	—	—	—	—	—	—	—	—	—	—		142
99.90	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	.15Cd	143
99.50	—	—	—	.01	.50	—	—	—	—	—	—	—	—	—	—		145
99.60	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	.40S	147
99.80	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	.15Zr	150
99.75	.07	—	—	.06	—	—	—	—	—	—	—	—	—	—	—	.11Mg	155
99.00	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1.00Cd	162
98.60	—	—	—	—	—	—	.60	—	—	—	—	—	—	—	—	.80Cd	165
98.30	—	—	—	—	—	.10	—	—	—	—	—	—	.10	.10	—	1.70Be	170
98.10	—	—	—	—	—	.10	—	—	—	—	—	—	.10	.10	—	1.90Be	172
97.70	—	—	—	—	—	.10	—	—	.40	—	—	—	.10	.10	—	1.90Be	173
96.90	—	—	—	—	—	.08	—	—	—	—	—	—	—	2.50	—	.60Be	175
99.10	—	—	—	—	—	.08	—	—	.05	—	.08	—	—	—	90		182
99.20	—	—	—	—	—	.10	—	.50	—	—	.08	—	—	—	.80		184
99.20	.10	—	—	—	—	—	—	—	.01	—	—	—	—	—	.70		185
99.00	—	—	—	—	—	—	—	—	1.00	—	—	—	—	—	—		187

COMPOSITION, %																	
Cu	Ag	As	Sb	P	Te	Fe	Sn	Zn	Pb	Al	Si	Mn	Ni	Co	Cr	Other	MATERIAL DESIGNATION
34. COPPER ALLOYS, WROUGHT (continued)																	
98.70	—	—	—	.05	—	—	.80	.10	.02	.01	.30	.20	—	—	—		189
98.60	—	—	—	.30	—	—	—	—	—	—	—	—	1.10	—	—		130
98.20	—	—	—	.20	.60	—	—	—	—	—	—	—	1.10	—	—		191
98.97	—	—	—	.03	—	1.00	—	—	—	—	—	—	—	—	—		192
97.40	—	—	—	.04	—	2.40	.03	.10	.03	—	—	—	—	—	—		194
97.00	—	—	—	.10	—	1.50	.60	—	—	—	—	—	—	.80	—		195
bal	—	—	—	—	—	.05	—	4.90	.05	—	—	—	—	—	—		210
bal	—	—	—	—	—	.05	—	9.90	.05	—	—	—	—	—	—		220
bal	—	—	—	—	—	.05	—	12.40	.05	—	—	—	—	—	—		226
bal	—	—	—	—	—	.05	—	14.90	.05	—	—	—	—	—	—		230
bal	—	—	—	—	—	.05	—	19.90	.05	—	—	—	—	—	—		240
bal	—	—	—	—	—	.05	—	29.90	.05	—	—	—	—	—	—		260
bal	—	—	—	—	—	.05	—	33.80	.15	—	—	—	—	—	—		268
bal	—	—	—	—	—	.05	—	34.85	.10	—	—	—	—	—	—		270
bal	—	—	—	—	—	.05	—	39.70	.25	—	—	—	—	—	—		280
bal	—	—	—	—	—	.10	—	9.00	1.90	—	—	—	—	—	—		314
bal	—	—	—	.10	—	.10	—	8.00	1.80	—	—	—	1.00	—	—		316
bal	—	—	—	—	—	.07	—	33.40	.50	—	—	—	—	—	—		330
bal	—	—	—	—	—	.07	—	32.30	1.60	—	—	—	—	—	—		332
bal	—	—	—	—	—	.10	—	34.40	.50	—	—	—	—	—	—		335
bal	—	—	—	—	—	.10	—	33.90	1.00	—	—	—	—	—	—		340
bal	—	—	—	—	—	.10	—	33.40	2.00	—	—	—	—	—	—		342
bal	—	—	—	—	—	.10	—	37.40	.30	—	—	—	—	—	—		349
bal	—	—	—	—	—	.10	—	36.40	1.00	—	—	—	—	—	—		350
bal	—	—	—	—	—	.10	—	36.10	1.80	—	—	—	—	—	—		353
bal	—	—	—	—	—	.10	—	35.40	2.50	—	—	—	—	—	—		356
bal	—	—	—	—	—	.25	—	35.25	3.00	—	—	—	—	—	—		360
bal	—	—	—	—	—	.15	.25	39.00	.60	—	—	—	—	—	—		365

COMPOSITION, %																	
Cu	Ag	As	Sb	P	Te	Fe	Sn	Zn	Pb	Al	Si	Mn	Ni	Co	Cr	Other	MATERIAL DESIGNATION
34. COPPER ALLOYS, WROUGHT (continued)																	
bal	—	.06	—	—	—	10	.20	39 00	.60	—	—	—	—	—	—		366
bal	—	—	.06	—	—	.10	20	39.00	60	—	—	—	—	—	—		367
bal	—	—	—	06	—	.10	.20	39.00	.60	—	—	—	—	—	—		368
bal	—	—	—	—	—	.10	—	38 50	1 00	—	—	-	—	—	—		370
bal	—	—	—	—	—	.25	—	37.75	2.00	—	—	—	—	—	—		377
bal	—	—	—	—	—	.30	—	39 70	3.00	—	—	—	—	—	—		385
90.00	—	—	—	—	—	05	.50	9 35	10	—	—	—	—	—	—		411
90.00	—	—	—	—	—	.05	1.00	.85	.10	—	—	—	—	—	—		413
88 50	—	—	—	20	—	.05	2 00	9 20	.05	—	—	—	—	—	—		425
81.00	—	—	—	—	—	.05	90	17 95	.10	—	—	—	—	—	—		435
72 00	—	—	—	—	—	.05	1 00	26.90	.07	—	—	—	—	—	—		442
71.00	—	07	—	—	—	06	1.00	27.80	.07	—	—	—	—	—	—		443
71.00	—	—	.07	—	—	.06	1.00	27 80	.07	—	—	—	—	—	—		444
71.00	—	—	—	07	—	06	1 00	27.80	07	—	—	—	—	—	—		445
60.00	—	—	—	—	—	.10	80	38.90	20	—	—	—	—	—	—		464
60.00	—	.07	—	—	—	.10	.80	38.80	.20	—	—	—	—	—	—		465
60.00	—	—	.07	—	—	.10	.80	38 80	.20	—	—	—	—	—	—		466
60.00	—	—	—	.07	—	.10	80	38.80	.20	—	—	—	—	—	—		467
60.50	—	—	—	—	—	10	.80	37.90	.70	—	—	—	—	—	—		482
60.00	—	—	—	—	—	.10	70	37 40	1.80	—	—	—	—	—	—		485
bal	—	—	—	.25	—	.10	1.10	.20	05	—	—	—	—	—	—		505
bal	—	—	—	.25	—	.10	5 00	20	05	—	—	—	—	—	—		510
bal	—	—	—	.25	—	.10	4.20	20	.05	—	—	—	—	—	—		511
bal	—	—	—	.25	—	10	8.00	.20	.05	—	—	—	—	—	—		521
bal	—	—	—	25	—	.10	10.00	.20	.05	—	—	—	—	—	—		524
bal	—	—	—	.40	—	10	4 00	4.00	4.00	—	—	—	—	—	—		544
bal	—	.25	—	—	—	10	—	—	.10	5 00	—	—	—	—	—		608
bal	—	—	—	—	—	.40	—	.20	.02	8 00	.10	—	—	—	—		610

COMPOSITION, %																	MATERIAL DESIGNATION
Cu	Ag	As	Sb	P	Te	Fe	Sn	Zn	Pb	Al	Si	Mn	Ni	Co	Cr	Other	
34. COPPER ALLOYS, WROUGHT (continued)																	
bal	—	—	—	—	—	2.00	.30	—	—	7.00	—	.50	.50	—	—		613
bal	—	—	—	.01	—	2.00	—	.20	.01	7.00	—	75	—	—	—		614
bal	—	—	—	—	—	1 00	—	.02	.02	10.00	.10	--	—	—	—		618
bal	—	—	—	—	—	4.00	.40	.60	02	9 00	—	—	—	—	—		619
bal	—	—	—	—	—	3.00	.40	—	—	10.00	.20	.50	1.00	—	—		623
bal	—	—	—	—	—	3.00	20	—	—	11.00	.20	.30	—	—	—		624
bal	—	—	—	—	—	4.00	—	—	—	13.00	—	2.00	—	—	—		625
bal	—	—	—	—	—	3.00	.20	20	—	10.00	20	1.00	4.00	—	—		630
bal	—	—	—	—	—	4.00	—	—	.02	9 00	.10	3.00	5.00	—	—		632
bal	—	—	—	—	—	.05	—	40	.05	2 80	1.80	10	.10	40	—		638
bal	—	.10	—	—	—	.25	.20	.40	.05	7.00	1.80	.10	25	—	—		642
bal	—	—	—	—	—	.60	—	1.00	.05	—	1.50	.70	—	—	—		651
bal	—	—	—	—	—	.60	—	1.00	.05	—	3.00	1.00	60	—	—		655
bal	—	—	—	—	—	.10	—	28 00	.07	—	—	1 20	—	—	—		667
bal	—	—	—	—	—	.25	20	35.00	.40	1.20	1.00	2 80	20	—	—		674
bal	—	—	—	—	—	1.40	1.00	38.00	.20	20	—	.10	—	—	—		675
bal	—	.10	—	—	—	06	—	20.00	.07	2.00	—	—	—	—	—		687
bal	—	—	—	—	—	.05	—	22.00	.05	3.40	—	—	—	.40	—		688
bal	—	—	—	—	—	.20	—	14.00	30	—	4.00	—	—	—	—		694
bal	—	—	—	—	—	1.40	—	.80	.05	—	—	.80	10 00	—	—		706
bal	—	—	—	—	—	.80	—	.80	.05	—	—	.80	20 00	—	—		710
bal	—	—	—	—	—	.50	—	.80	05	—	—	.80	30.00	—	—		715
bal	—	—	—	—	—	.40	2 30	.50	.05	—	—	.20	9.50	—	—		725
bal	—	—	—	—	—	.20	—	24.00	.05	—	—	.50	10.00	—	—		745
bal	—	—	—	—	—	.20	—	16.00	05	—	—	.50	18.00	—	—		752
bal	—	—	—	—	—	.20	—	19.00	.10	—	—	.50	15.00	—	—		754
bal	—	—	—	—	—	.20	--	22.00	.05	—	—	.50	12.00	—	—		757
bal	—	—	—	—	—	.20	—	26.00	.05	—	--	.50	18.00	—	—		770
					—	.30	—	24.00	2.00	—	—	.50	8.00	--	—		782

COMPOSITION, %																	MATERIAL DESIGNATION
Cu	Ag	As	Sb	P	S	Fe	Sn	Zn	Pb	Al	Si	Mn	Ni	Co	Cr	Other	
35. COPPER ALLOYS, CAST																	
99.95	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		801
99.75	.03	—	—	—	—	—	—	—	—	—	—	—	—	—	—		803
99.75	.03	—	—	—	—	—	—	—	—	—	—	—	—	—	—	.01B	805
99.75	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	01B	807
99.70	.03	—	—	—	—	—	—	—	—	—	—	—	—	—	—		809
99.70	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		811
bal	—	—	—	—	—	—	—	—	—	—	—	—	—	80	—	.06Be	813
bal	—	—	—	—	—	—	—	—	—	—	—	—	—	—	.80	06Be	814
bal	—	—	—	—	—	05	.05	.05	.02	.05	.10	—	—	—	1 00		815
bal	1.00	—	—	—	—	—	—	—	—	—	—	—	.90	.90	—	40Be	817
bal	1.00	—	—	—	—	—	—	—	—	—	—	—	—	1.60	—	40Be	818
bal	—	—	—	—	—	.05	.05	.05	.02	.05	.10	—	.10	2.40	.05	.60Be	820
bal	—	—	—	—	—	—	—	—	—	—	—	—	90	90	—	50Be	821
bal	—	—	—	—	—	—	—	—	—	—	—	—	1.50	—	—	.60Be	822
bal	—	—	—	—	—	.10	05	.05	.02	.10	—	—	10	.25	.05	1 70Be	824
bal	—	—	—	—	—	.15	.05	.05	.02	.10	.25	—	.10	.45	.05	2.00Be	825
bal	—	—	—	—	—	.15	.05	.05	.02	.10	.25	—	.10	.50	.05	2.30Be	826
bal	—	—	—	—	—	.15	.05	.05	.02	10	10	—	1.25	—	05	2 45Be	827
bal	—	—	—	—	—	.15	.05	.05	.02	10	.25	—	10	45	05	2 60Be	828
bal	—	—	—	—	—	—	1.50	4.00	1.50	—	—	—	—	—	—		833
bal	—	—	—	—	—	—	.10	10.00	.25	—	—	—	—	—	—		834
bal	—	—	.20	.05	.04	.20	5.00	5.00	5.00	.005	.005	—	50	—	—		836
bal	—	—	20	.03	.04	.20	4.00	7.00	6.00	.005	.005	—	50	—	—		838
bal	—	—	.20	.03	.04	.30	5.00	12.50	2.50	.005	.005	—	40	—	—		842
bal	—	—	.20	.02	.04	.30	3.00	9.00	7.00	005	.005	—	.50	—	—		844
bal	—	—	.20	.02	.04	.30	3.00	15.00	6.00	005	.005	—	.50	—	—		848
bal	—	—	.15	.02	.03	.40	1.00	24.00	3.00	005	.05	—	.50	—	—		852
bal	—	—	—	—	—	—	.40	28.00	.40	—	—	—	—	—	—		853
bal	—	—	—	—	—	.50	1.00	27.00	3.00	.20	05	—	—	—	—		854

COMPOSITION, %																	MATERIAL DESIGNATION
Cu	Ag	As	Sb	P	S	Fe	Sn	Zn	Pb	Al	Si	Mn	Ni	Co	Cr	Other	
35. COPPER ALLOYS, CAST (continued)																	
bal	—	—	—	—	—	.10	.10	34.00	.10	.80	—	.10	.10	—	—		855
bal	—	—	—	—	—	.60	1.00	32.00	1.00	.30	.05	—	.50	—	—		857
bal	—	.05	.05	.01	.05	.40	1 00	39.00	1.00	.25	.20	.20	—	—	--		858
bal	—	—	—	—	—	3.00	.20	20.00	.20	5.00	—	4.00	—	—	—		861
bal	—	—	—	—	—	3.00	.20	25.00	.20	4.00	—	3.00	.50	—	—		862
bal	—	—	—	—	—	3.00	.20	23.00	.20	6 00	—	3.00	—	—	—		863
bal	—	—	—	—	—	1.00	.75	37 00	1.00	.75	—	.75	—	—	—		864
bal	—	—	—	—	—	1.00	.50	38.00	25	1.00	—	1.00	.25	—	—		865
bal	—	—	—	—	—	1.50	1.00	36.00	1.00	1.50	—	2.00	.50	—	—		867
bal	—	—	—	—	—	2.00	.50	36.00	.10	1.00	—	3.00	3.00	—	—		868
bal	—	—	—	—	—	2.00	.50	4.00	.25	1 00	4.00	1.00	—	—	—		872
bal	—	—	—	—	—	—	—	14.00	.50	.40	3.00	—	—	—	—		874
bal	—	—	—	—	—	—	—	14.00	.25	.25	4.00	—	—	—	—		875
bal	—	—	—	—	—	—	—	6.00	.25	—	5.00	—	—	—	—		876
bal	—	.05	.05	.01	.05	.10	.20	14.00	.10	.10	4.00	.10	.10	—	—		878
bal	—	.05	.05	.01	.05	.20	.20	33.00	.20	.10	1.00	.10	.25	—	—		879
bal	—	—	.10	.05	.05	.10	7.00	.30	.20	.005	.005	—	.25	—	—		902
bal	—	—	.10	.05	.05	.10	8.00	4.00	.20	.005	.005	—	.50	—	—		903
bal	—	—	.10	.05	.05	.10	10.00	2.00	.20	.005	.005	—	.50	—	—		905
bal	—	—	.10	.20	.05	.10	11.00	.30	.40	.005	.005	—	.25	—	—		907
bal	—	—	.10	.05	.05	.10	13.00	.20	.20	.005	.005	—	.25	—	—		909
bal	—	—	.10	.05	.05	.10	15.00	1.00	.10	.005	.005	—	.40	--	—		910
bal	—	—	.10	.50	.05	.20	16.00	.20	.15	.005	.005	—	.25	—	—		911
bal	—	—	.10	.50	.05	.20	19.00	.20	.15	.005	.005	—	.25	—	—		913
bal	—	—	.10	.25	.05	.10	10.00	.20	2.50	.005	.005	—	3.50	—	—		915
bal	—	—	.15	.20	.05	.15	10.50	.20	.20	.005	.005	—	1.50	—	—		916
bal	--	—	.10	.25	.05	.10	12.00	.20	.20	.005	.005	—	1.50	—	—		917
bal	—	—	.15	.05	.05	.20	6.00	4.50	1.50	.005	.005	—	.50	—	—		922

COMPOSITION, %																
Cu	Ag	As	Sb	P	S	Fe	Sn	Zn	Pb	Al	Si	Mn	Ni	Co	Cr	Other	MATERIAL DESIGNATION
35. COPPER ALLOYS, CAST (continued)																	
bal	—	—	.15	.05	.05	.20	8.00	4.00	.50	005	.005	—	.50	—	—		923
bal	—	—	.15	.25	.05	10	11.00	.25	1.00	.005	.005	—	1.00	—	—		925
bal	—	—	.15	.03	.05	.10	10.00	2.00	1.00	.005	005	—	.40	—	—		926
bal	—	—	.15	.20	.05	.10	10.00	.50	2 00	.005	.005	—	.50	—	—		927
bal	—	—	.15	.05	05	.10	16.00	.40	5.00	.005	.005	—	.40	—	—		928
bal	—	—	.25	.10	.04	.10	7.00	3.00	7 00	.005	005	—	.50	—	—		932
bal	—	—	.35	.30	.04	.10	8 00	.40	8.00	.005	005	—	.50	—	—		934
bal	—	—	.20	.05	.04	.10	5.00	1.00	9.00	.005	.005	—	.50	—	—		935
bal	—	—	.40	.10	.04	.10	10.00	.40	10.00	.005	.005	—	.50	—	—		937
bal	—	—	40	.05	04	.10	7.00	.40	15.00	.005	.005	—	.50	—	—		938
bal	—	—	.35	.75	.04	.20	6.00	.80	15 00	.005	.005	—	.40	—	—		939
bal	—	—	.40	.05	.04	.10	5.00	.40	25.00	.005	.005	—	.50	—	—		943
bal	—	—	.40	.35	.04	.10	8.00	.40	11.00	.005	.005	—	.50	—	—		944
bal	—	—	.40	.05	.04	.10	7.00	.60	20.00	.005	.005	—	.50	—	—		945
bal	—	—	.10	.05	.05	.15	5.00	2.00	.05	.005	.005	.10	5.00	—	—		947
bal	—	—	.10	.05	.05	.15	5.00	2.00	.65	.005	.005	.10	5.00	—	—		948
bal	—	—	—	—	—	3.00	—	—	—	9.00	—	—	—	—	—		952
bal	—	—	—	—	—	1.00	—	—	—	10.00	—	—	—	—	—		953
bal	—	—	—	—	—	4.00	—	—	—	11.00	—	.25	1.50	—	—		954
bal	—	—	—	—	—	4.00	—	—	—	11.00	—	2.50	4.00	—	—		955
bal	—	—	—	—	—	—	—	—	—	7.00	2.00	—	.15	—	—		956
bal	—	—	—	—	—	3.00	—	—	.03	8.00	.10	12.00	2.00	—	—		957
bal	—	—	—	—	—	4.00	—	—	.03	9.00	.10	1.00	4.00	—	—		958
bal	—	—	—	—	—	1.40	—	—	.02	—	.15	1.00	10.00	—	—	.50Cb	962
bal	—	—	—	—	—	.70	—	—	.02	—	.40	.50	20.00	—	—	50Cb	963
bal	—	—	—	—	—	.90	—	—	.02	—	.40	1.00	30.00	—	—	.50Cb	964
bal	—	—	—	—	—	1.00	—	—	.01	—	.10	.50	30.00	—	—	.50Be	966
bal	—	—	.20	.05	.04	75	2.00	20.00	10.00	.005	.10	.25	12.00	—	—		973

COMPOSITION, %																	
Cu	Ag	As	Sb	P	S	Fe	Sn	Zn	Pb	Al	Si	Mn	Ni	Co	Cr	Other	MATERIAL DESIGNATION
35. COPPER ALLOYS, CAST (continued)																	
bal	—	—	—	—	—	.75	3.00	16.00	5.00	—	—	.25	17.00	—	—		974
bal	—	—	.15	.05	.04	.75	4.00	8.00	4.00	005	10	.50	20.00	—	—		976
bal	—	—	.10	.05	.04	.75	5.00	2.00	2.00	.005	.10	.50	25.00	—	—		978
bal	—	—	—	—	—	.70	.05	—	.02	11.00	.02	—	15.00	1.50	—		993

COMPOSITION, %																	
Ni	C	Mn	Fe	Si	Cu	Mg	Ti	Al	P	S	—	—	—	—	—	Other	MATERIAL DESIGNATION
36. NICKEL ALLOYS, WROUGHT AND CAST																	
bal	—	.40	48.50	.50	—	—	2.55	.55	—	—						5.30Cr	NI-SPAN-C 902
bal	—	.50	.60	1.00	—	—	.60	4.35	—	—							DURANICKEL Alloy 301
bal	—	.75	1.00	—	28.00	—	—	3.00	—	—							MONEL Alloy 502
bal	—	1.00	1.25	.25	31.50	—	—	—	—	—							MONEL Alloy 400
bal	.01	.18	.20	.18	.13	—	—	—	—	—							Nickel 201
bal	.04	.10	.05	.03	.05	.05	.03	—	—	—							Nickel 220
bal	.05	.08	—	.02	.05	.06	—	—	—	—							Nickel 230
bal	.05	1.60	.38	.13	55.00	—	—	—	—								MONEL Alloy 401
bal	.08	—	.25	.05	44.00	—	—	.03	—	—							MONEL Alloy 404
bal	.08	.18	.10	.08	.08	.05	.03	—	—	—							Nickel 205
bal	.08	.18	.20	.18	.13	—	—	—	—	—							Nickel 200
bal	.10	4.75	.38	.08	.13	—	—	—	—	—							Nickel 211
bal	.13	.75	1.00	—	29.50	—	.60	2.70	—	—							MONEL Alloy K500
bal	.15	1.00	1.25	.25	31.50	—	—	—	—	—							MONEL Alloy R405
bal	.20	.25	.30	.18	.13	.35	.40	—	—	—							PERMANICKEL Alloy 300
bal	.35	1.50	3.50	2.00	30.00	—	—	—	.03	.03							ASTM A296 Grade M-35
bal	.35	1.50	3.50	2.00	30.00	—	—	—	.03	.03							ASTM A494 Grade M-35
bal	1.00	1.50	3.00	2.00	1.25	—	—	—	.03	.03							ASTM A296 Grade CZ-100
bal	1.00	1.50	3.00	2.00	1.25	—	—	—	.03	.03							ASTM A494 Grade CZ-100

COMPOSITION, %																		
Ni	C	Be	Ti	Cr	—	—	—	—	—	—	—	—	—	—	—	Other	MATERIAL DESIGNATION
37. BERYLLIUM NICKEL ALLOYS, WROUGHT AND CAST																		
bal	—	2.20	—	—														
bal	—	1.95	.50	—													Brush Alloy 200C	
bal	.60	2.20	—	—													Berylco 440	
bal	.30	2.70	—	—													Brush Alloy 220C	
bal	.10	2.75	—	.40													Brush Alloy 260C	
bal	.10	2.75	—	6.00													Berylco 41C	
bal	.10	2.75	—	12.00													Berylco 43C	
																	Berylco 42C	

COMPOSITION, %																		
Ni	Ti	—	—	—	—	—	—	—	—	—	—	—	—	—	—	Other	MATERIAL DESIGNATION
38. NITINOL ALLOYS, WROUGHT																		
bal	40.00																	
bal	44.00																Nitinol 60Ni-40Ti	
bal	45.00																Nitinol 56Ni-44Ti	
																	Nitinol 55Ni-45Ti	

COMPOSITION, %																			
Ni	Cr	Co	Mo	W	Ta	Cb	Al	Ti	Fe	Mn	Si	C	B	Zr	Cu	Other	MATERIAL DESIGNATION
39. HIGH TEMPERATURE ALLOYS — Nickel Base, Wrought																		
bal	1.00	1.00	28.00	—	—	—	—	—	2.00	.50	.05	.02	—	—	—			
bal	1.50	2.00	28.00	—	—	—	—	—	5.00	.50	.50	.05	—	—	—		Hastelloy Alloy B-2	
bal	12.00	10.00	3.00	6.00	1.50	—	4.60	3.00	.30	.05	.05	.35	.01	.10	—	.40V	Hastelloy Alloy B	
bal	13.00	—	6.00	—	—	—	.20	2.80	34.00	.40	.40	.05	.01	—	—		AF2-1DA	
bal	14.00	8.00	3.50	3.50	—	3.50	3.50	2.50	—	—	—	.15	.01	.05	—		Incoloy Alloy 901	
bal	14.00	15.00	6.00	3.50	—	—	3.80	2.50	.50	.10	.20	.05	.01	—	—		Rene 95	
																	Rene 63	

COMPOSITION, %																	
Ni	Cr	Co	Mo	W	Ta	Cb	Al	Ti	Fe	Mn	Si	C	B	Zr	Cu	Other	MATERIAL DESIGNATION
39. HIGH TEMPERATURE ALLOYS — Nickel Base, Wrought (continued)																	
bal	15.00	—	3.00	3.00	3.00	*	.50	.60	7.00	—	—	04	.01	.03	—	.04Mg	IN-102
bal	15.00	2.00	17.00	5.00	—	—	—	—	6.00	—	—	.04	—	—	—		Hastelloy Alloy C
bal	15.00	15.00	4.20	—	—	—	4.30	3.30	.40	.10	.10	.07	.01	.04	—		Rene 77
bal	15.00	17.00	5.25	—	—	—	4.40	3.50	—	—	—	.06	.03	—	—		Astroloy
bal	15.00	18.50	5.20	—	—	—	4.30	3.50	—	—	—	.08	.03	—	—		Udimet 700
bal	15.00	28.50	3.70	—	—	—	3.00	2.20	.70	10	.30	.12	—	—	—		Inconel Alloy 700
bal	15.50	—	—	—	—	—	—	—	8.00	.50	.20	.08	—	—	—		Inconel Alloy 600
bal	15.50	—	—	—	—	—	.70	2.35	7.00	.50	.35	.04	—	—	—		Inconel Alloy 722
bal	15.50	—	—	—	—	—	1.20	2.30	7.00	.50	.25	.05	—	—	.25		Inconel Alloy 751
bal	15.50	—	—	—	—	1.00	.70	2.50	7.00	.50	.20	.04	—	—	—		Inconel Alloy X-750
bal	15.50	1.50	14.50	—	—	—	.20	—	1.00	.50	.40	.01	.01	—	—	.02La	Hastelloy Alloy S
bal	15.50	2.00	16.00	4.00	—	—	—	—	6.00	.50	.05	.02	—	—	—	.35V	Hastelloy Alloy C-276
bal	15.60	—	—	—	—	—	3.40	.70	.40	.05	.20	.04	—	—	—		Inconel Alloy 702
bal	16.00	—	—	—	—	—	.10	3.00	8.00	2.25	.15	.07	—	—	.20		Inconel Alloy 721
bal	16.00	—	—	—	—	2.90	.20	1.80	40.00	.20	.20	.03	—	—	—		Inconel Alloy 706
bal	16.25	7.20	1.60	8.40	—	—	1.90	3.20	9.50	.05	.10	.24	.01	.06	—		Unitemp 1753
bal	18.00	—	3.00	3.00	—	6.50	.50	1.00	18.00	—	—	.03	—	—	—		Udimet 630
bal	18.00	15.00	3.00	1.50	—	—	2.50	5.00	—	—	—	.07	.02	—	—		Udimet 710
bal	18.00	18.50	4.00	—	—	—	2.90	2.90	—	—	—	.08	.01	.05	—		Udimet 500
bal	18.00	20.00	3.20	—	—	—	.20	2.60	18.00	.80	1.00	.03	—	—	—		Refractaloy 26
bal	19.00	—	3.00	—	—	5.00	.50	.90	18.50	.20	.20	.04	—	—	—		Inconel Alloy 718
bal	19.00	11.00	10.00	—	—	—	1.50	3.10	—	—	—	.09	.01	—	—		Rene 41
bal	19.50	—	—	—	—	—	—	.40	8.00	.50	.50	.10	—	—	—		Nimonic 75
bal	19.50	2.00	—	—	—	—	.65	2.25	5.00	.50	.50	.06	—	—	—		Nimonic 80
bal	19.50	13.50	4.30	—	—	—	1.30	3.00	—	—	—	.08	.01	.06	—		Waspaloy

*Included with tantalum.

COMPOSITION, %																	
Ni	Cr	Co	Mo	W	Ta	Cb	Al	Ti	Fe	Mn	Si	C	B	Zr	Cu	Other	MATERIAL DESIGNATION
39. HIGH TEMPERATURE ALLOYS — Nickel Base, Wrought (continued)																	
bal	19.50	16.50	—	—	—	—	1.45	2.45	5.00	.50	.75	.07	.003	.06	—		Nimonic 90
bal	19.50	18.00	—	—	—	—	2.00	3.50	5.00	1.00	1.00	.10	—	—	—		Nimonic 95
bal	20.00	10.00	10.00	—	—	—	1.00	2.60	—	.50	.50	.15	.01	—	—		M252
bal	20.00	20.00	6.00	—	—	—	.50	2.00	.60	.50	.30	.06	—	—	.20		Haynes Alloy 263
bal	21.50	—	—	3.00	—	—	.20	.90	30.00	.65	.50	.03	—	—	2.25		Incoloy Alloy 825
bal	21.50	—	9.00	—	—	3.60	.20	.20	2.50	.20	.20	.05	—	—	—		Inconel Alloy 625
bal	21.80	1.50	9.00	.60	—	—	—	—	18.50	.50	.50	.10	—	—	—		Hastelloy Alloy X
bal	22.00	2.00	6.50	.50	2.10	*	—	—	19.50	1.50	.50	.03	—	—	2.00		Hastelloy Alloy G
bal	22.00	12.50	9.00	—	—	—	1.00	—	—	—	—	.07	—	—	—		Inconel Alloy 617
bal	23.00	—	—	—	—	—	1.40	—	14.10	.50	.20	.05	—	—	—		Inconel Alloy 601
bal	29.50	—	—	—	—	—	.25	.60	25.40	.75	.50	.06	—	—	.40		Incoloy Alloy 804
bal	—	15.00	—	—	—	3.00	.70	1.40	42.00	—	—	—	—	—	—		Incoloy Alloy 903
bal	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	$2.00ThO_2$	TD-Nickel
bal	20.00	—	—	—	—	—	—	—	—	—	—	.10	—	—	—	$2.00ThO_2$	TD-Ni-Cr
39. HIGH TEMPERATURE ALLOYS — Nickel Base, Cast																	
bal	.70	—	28.00	—	—	—	—	—	5.00	.70	.70	.10	—	—	—	.50V	ASTM A494 Grade N-12M-1
bal	.70	—	30.00	—	—	—	—	—	5.00	.70	.70	.10	—	—	—	.50V	ASTM A296 Grade N-12M
bal	.70	—	32.00	—	—	—	—	—	2.50	.70	.70	.05	—	—	—		ASTM A494 Grade N-12M-2
bal	.70	2.00	28.00	—	—	—	—	—	5.00	.70	.70	.10	—	—	—	.50V	Hastelloy Alloy B
bal	1.00	—	—	—	—	—	—	—	2.00	1.00	9.00	.12	—	—	3.00		Hastelloy Alloy D
bal	6.00	7.50	2.00	5.80	9.00	.50	5.40	1.00	—	—	—	.13	.02	.13	—	.50Re, .43Hf	TRW VI A
bal	7.00	.10	16.50	.40	—	—	.40	—	4.00	.60	.70	.06	.01	—	.30		Hastelloy Alloy N
bal	8.00	10.00	6.00	.05	—	.05	6.00	1.00	.30	.15	.20	.10	.02	.08	—		B-1900
bal	8.90	10.00	2.00	7.00	3.80	—	4.75	2.50	—	—	—	.10	.02	.05	—	1.50Hf	Rene 125
bal	9.00	10.00	—	12.50	—	1.00	5.00	2.00	—	—	—	.15	.02	.05	—		MAR-M200

*Included with tantalum.

COMPOSITION, %																	
Ni	Cr	Co	Mo	W	Ta	Cb	Al	Ti	Fe	Mn	Si	C	B	Zr	Cu	Other	MATERIAL DESIGNATION
39. HIGH TEMPERATURE ALLOYS — Nickel Base, Cast (continued)																	
bal	9.00	10.00	2.50	10.00	1.50	--	5.50	1.50	--	--	--	.15	.02	.05	--		MAR-M246
bal	10.00	15.00	3.00	--	--	--	5.50	4.70	--	--	--	.18	.01	.06	--	1.00V	IN-100 (Rene 100)
bal	10.50	13.50	6.15	1.50	.50	--	5.50	2.50	.40	--	--	.08	.02	--	--		SEL 15
bal	12.00	--	.50	--	--	--	--	--	--	1.00	1.50	.55	--	--	--		ASTM A297 Grade HW
bal	12.00	--	.50	--	--	--	--	--	--	1.00	1.50	.50	--	--	--		ASTM A608 Grade HW50
bal	12.40	9.00	1.90	3.80	3.90	--	3.10	4.50	--	--	--	.12	.02	.10	--		IN-792
bal	12.50	--	4.50	--	2.00	*	6.00	.75	5.00	1.00	1.00	.20	--	--	--		Inconel Alloy 713C
bal	14.00	9.50	4.00	4.00	--	--	3.00	5.00	--	--	--	.17	.02	03	--		Rene 80
bal	15.00	--	17.00	5.00	--	--	--	--	6.00	.70	.70	.08	--	--	--		Hastelloy Alloy C
bal	15.00	18.50	5.20	--	--	--	4.30	3.50	--	--	--	.08	.03	--	--		Udimet 700
bal	15.00	22.00	4.40	--	--	--	4.35	2.35	.70	--	--	.08	.02	--	--		SEL
bal	15.50	--	--	--	--	--	--	--	10.00	1.00	2.00	.30	--	--	--		ASTM A296 Grade CY-40
bal	15.50	--	--	--	--	--	--	--	10.00	1.00	2.00	.30	--	--	--		ASTM A494 Grade CY-40
bal	15.50	--	5.25	--	--	--	3.00	2.00	10.00	.20	.40	.15	.06	--	--		GMR-235
bal	15.50	--	5.00	--	--	--	3.50	2.50	4.50	.05	.20	.15	.05	--	--		GMR-235D
bal	15.50	10.00	1.75	3.50	--	1.75	4.25	1.75	--	--	--	.15	.02	.05	--		MAR-M421
bal	15.50	20.00	--	3.00	2.00	2.00	2.80	4.30	--	--	--	.15	.02	.05	--		MAR-M432
bal	16.00	8.50	1.75	2.60	1.75	.90	3.40	3.40	.40	.10	.15	.17	.01	.10	--		IN-738
bal	16.50	--	17.00	5.00	--	--	--	--	6.00	.70	.70	.10	--	--	--	.30V	ASTM A494 Grade CW-12M-1
bal	17.00	--	.50	--	--	--	--	--	--	1.00	1.50	.55	--	--	--		ASTM A297 Grade HX
bal	17.00	--	.50	--	--	--	--	--	--	1.00	1.50	.50	--	--	--		ASTM A608 Grade HX50
bal	18.00	--	18.00	5.00	--	--	--	--	7.00	.70	1.00	.10	--	--	--	.40V	ASTM A296 Grade CW-12M
bal	18.60	--	3.10	--	--	5.00	.40	.90	18.50	.20	.30	.04	--	--	--		Inconel Alloy 718
bal	19.00	--	19.00	--	--	--	--	--	2.50	.70	.70	.05	--	--	--		ASTM A494 Grade CW-12M-2
bal	19.00	10.00	10.00	--	--	--	1.00	2.60	--	.40	.40	.15	.01	--	--		M252
bal	19.00	18.00	4.20	--	--	--	3.00	3.00	--	--	--	.08	.01	.05	--		Udimet 501

*Included with tantalum.

COMPOSITION, %																	
Ni	Cr	Co	Mo	W	Ta	Cb	Al	Ti	Fe	Mn	Si	C	B	Zr	Cu	Other	MATERIAL DESIGNATION
39. HIGH TEMPERATURE ALLOYS — Cobalt Base, Wrought																	
—	19.00	bal	—	4.70	6.50	—	3.50	—	—	—	—	.18	—	.15	—	.10Y	AiResist 213
10.00	20.00	bal	—	15.00	—	—	—	—	—	1.50	.50	.10	—	—	—		Haynes Alloy 25 (L605)
20.00	20.00	bal	—	—	7.50	—	—	.50	—	—	—	.05	—	.10	—		MAR-M905
20.00	20.00	bal	—	—	7.50	—	—	—	.40	.10	.10	.05	—	.10	—		MAR-M918
20.00	20.00	bal	4.00	4.00	—	—	—	—	4.00	1.20	.40	.38	—	—	—		S-816
20.00	25.00	bal	4.00	2.00	—	2.00	—	—	3.00	1.00	.40	.26	—	—	—		V-36
22.00	22.00	bal	—	14.00	—	—	—	—	2.50	1.00	.40	.10	—	—	—	.08La	Haynes Alloy 188
28.00	20.00	bal	—	7.00	—	—	—	4.00	2.00	—	—	—	—	—	—		J-1570
39. HIGH TEMPERATURE ALLOYS — Cobalt Base, Cast																	
—	3.00	bal	—	25.00	—	—	—	1.00	—	—	—	.40	—	1.00	—	2.00Re	NASA Co-W-Re
—	19.00	bal	—	4.50	7.50	—	4.30	—	—	—	—	.35	—	.13	—	.17Y	AiResist 215
—	21.50	bal	—	10.00	9.00	—	—	—	—	—	—	.85	.01	.20	—		MAR-M302
—	21.50	bal	—	9.00	4.50	—	—	.75	—	.10	.10	1.00	—	2.25	—		MAR-M322
.70	21.00	bal	—	11.00	—	2.00	3.50	—	2.00	.40	—	.45	—	—	—	.10Y	AiResist 13
1.00	21.00	bal	—	11.00	—	2.00	—	—	2.00	.25	.25	.45	—	—	—		WI-52
2.50	28.00	bal	—	5.00	—	—	—	—	3.00	—	—	1.00	—	—	—		HS-6
3.00	27.00	bal	5.00	—	—	—	—	—	1.00	.60	.60	.25	.01	—	—		HS-21
3.00	31.00	bal	—	12.50	—	—	—	—	3.00	1.00	1.00	2.45	—	—	—		HOWMET #3
10.00	23.50	bal	—	7.00	3.50	—	—	.20	1.00	.10	.10	.60	.01	.50	—		MAR-M509
10.00	25.00	bal	—	7.50	—	—	—	—	1.50	.75	.75	.50	—	—	—		HS-31 (X-40)
10.00	29.00	bal	—	7.00	—	—	—	—	1.50	.70	.70	.25	.01	—	—		FSX-414
10.50	25.50	bal	—	7.00	—	—	—	—	2.00	.70	—	.25	.01	—	—		X-45

COMPOSITION, %																	MATERIAL DESIGNATION
Ni	Cr	Co	Mo	W	Ta	Cb	Al	Ti	Fe	Mn	Si	C	B	Zr	Cu	Other	
39. HIGH TEMPERATURE ALLOYS — Iron Base, Wrought																	
9.00	19.00	—	1.00	1.00	—	—	—	—	bal	1.10	.60	.30	—	—	—		19-9DL
20.00	21.00	20.00	3.00	2.50	--	1.00	—	—	bal	1.50	.50	.15	—	—	—	.15N	N-155
25.00	16.00	—	6.00	—	—	.40	—	.30	bal	1.35	.70	.12	—	—	—		16-25-6
26.00	13.50	—	1.50	—	—	—	.20	2.85	bal	1.50	.40	.08	.08	—	—		W-545
26.00	13.50	—	2.70	—	—	—	.10	1.70	bal	.90	.80	.04	.01	—	--		Discaloy
26.00	15.00	—	1.30	—	—	—	.20	2.00	bal	1.35	.50	.05	.02	—	—		A-286
27.00	14.80	—	1.25	--	—	—	.25	3.00	bal	.35	.75	.08	.01	—	—	.50V	V-57
32.00	20.50	--	—	—	—	—	—	1.10	bal	.80	.50	.05	—	—	—		Incoloy Alloy 801
32.50	21.00	—	—	—	—	—	.40	.40	bal	.80	.50	.05	—	—	—		Incoloy Alloy 800
32.50	21.00	—	—	—	—	—	.40	.40	bal	.80	.50	.08	—	—	.40	.008S	Incoloy Alloy 800H
32.50	21.50	--	—	—	—	—	—	—	bal	.80	.40	.40	--	—	—		Incoloy Alloy 802

COMPOSITION, %																	MATERIAL DESIGNATION
W	Mo	Cb	Ta	Hf	Zr	Ti	Ni	Fe	Cu	Re	C	—	—	—	—	Other	
40. REFRACTORY ALLOYS, WROUGHT, CAST, P/M — Columbium																	
—	—	bal	—	10.00	.50	1.00	—	—	—	—	—						C103
10.00	—	bal	—	10.00	—	—	—	—	—	—	—					.10Y	C129Y
—	—	bal	—	—	1.00	—	—	—	—	—	—						Cb-1Zr
10.00	—	bal	—	—	2.50	—	—	—	—	—	—						Cb-752
11.00	—	bal	28.00	—	1.00	—	—	—	—	—	—						FS-85
10.0.	—	bal	10.00	—	—	—	—	—	—	—	.01					$.01O_2$, .01N	FS-291
13.50	—	bal	—	29.00	1.00	—	—	—	—	—	.30						WC-3015

COMPOSITION, %																	
W	Mo	Cb	Ta	Hf	Zr	Ti	Ni	Fe	Cu	Re	C	—	—	—	—	Other	MATERIAL DESIGNATION
40. REFRACTORY ALLOYS, WROUGHT, CAST, P/M — Molybdenum																	
—	99.00	—	—	--	—	—	—	—	—	—	—						Mo
—	bal	—	—	—	—	—	—	—	—	50.00	—						Mo-50Re
—	bal	—	—	—	.30	1.25	—	—	—	—	—						TZC
—	bal	—	—	—	.08	.50	—	—	—	—	—						TZM
40. REFRACTORY ALLOYS, WROUGHT, CAST, P/M — Tantalum																	
8.00	—	—	bal	1.00	—	—	—	—	—	1.00	.02						ASTAR 811C
5.00	—	—	bal	2.40	—	—	—	—	—	—	—						T-111
9.50	—	—	bal	2.40	—	—	—	—	—	—	.01						T-222
10.00	—	—	bal	—	—	—	—	—	—	—	—						Ta-10W
—	—	—	bal	1.00	—	—	—	—	—	--	—						Ta-Hf
2.50	—	.15	bal	—	—	—	—	—	—	—	—						Ta63
40. REFRACTORY ALLOYS, WROUGHT, CAST, P/M — Tungsten Alloys																	
bal	—	—	—	—	—	—	—	—	--	—	—						
bal	4.00	—	—	—	—	—	4.00	2.00	--	—	—					doped	GE-218
bal	4.00	—	—	—	—	—	4.00	2.00	--	—	—						Anviloy 1100
bal	4.00	—	—	—	—	—	4.00	2.00	--	—	—						Anviloy 1150
bal	*	—	—	—	—	—	3.00	*	7.00*	—	—						Anviloy 1200
bal	—	—	—	—	—	—	5.00†	—	†	—	—						Gyromet
bal	—	—	—	—	—	—	—	--	—	—	—						Mallory 2000
bal	15.00	—	—	—	—	—	—	—	—	—	—					10.00Ag	W-10Ag
bal	--	—	—	—	—	—	7.00	—	4.00	—	—						W-15Mo
bal	—	—	—	—	—	—	—	—	--	5.00	—						W-7Ni-4Cu
bal	—	—	—	—	--	—	—	—	—	25.00	—						W-5Re
bal	30.00	—	—	—	—	—	—	--	—	25.00	—						W-25Re
																	W-25Re-30Mo

*7.00 Cu + Mo + Fe.
†5/30 Ni + Cu.

COMPOSITION, %																	MATERIAL DESIGNATION
Zn	Al	Mg	Cu	Fe	Pb	Cd	Sn	—	—	—	—	—	—	—	—	Other	
41. ZINC ALLOYS, CAST																	
bal	3.90	—	.25	—	—	—	—										ZDC No. 7
bal	12.00	.02	.50	—	—	—	—										ILZRO 12
bal	3.90	.04	.08	.08	.01	.01	.01										AMS 4803
bal	3.90	04	.20	.08	.01	.01	.01										SAE J469a Grade 903 (AG40A)
bal	3.90	.05	1.00	.10	.01	.01	.01										SAE J469a Grade 925 (AC41A)

COMPOSITION, %																	MATERIAL DESIGNATION
Pb	Sn	Sb	Cu	Fe	As	Bi	Zn	Al	Cd	—	—	—	—	—	—	Other	
42. LEAD ALLOYS, CAST																	
bal	—	1.00	—	—	—	—	—	—	—								1Sb
bal	—	4.00	—	—	—	—	—	—	—								4Sb
bal	—	6.00	—	—	—	—	—	—	—								6Sb
bal	—	8.00	—	—	—	—	—	—	—								8Sb
bal	—	9.00	—	—	—	—	—	—	—								9Sb
bal	1.00	16.00	.60	.10	1.10	.10	.01	.01	.05								ASTM B23 Alloy 15
bal	5.00	15.00	.50	.10	.50	.10	.01	.01	.05								ASTM B23 Alloy 8
bal	6.00	10.00	.50	.10	.25	.10	.01	.01	.05								ASTM B23 Alloy 13
bal	10.00	15.00	.50	.10	.50	.10	.01	.01	.05								ASTM B23 Alloy 7

COMPOSITION, %																	MATERIAL DESIGNATION
Sn	Sb	Pb	Cu	Fe	As	Bi	Zn	Al	Cd	—	—	—	—	—	—	Other	
43. TIN ALLOYS, CAST																	
bal	4.50	.35	4.50	.08	.10	.08	.01	.01	.05								ASTM B23 Alloy 1
bal	7.50	.35	3.50	.08	.10	.08	.01	.01	.05								ASTM B23 Alloy 2
bal	8.00	.35	8.00	.08	.10	.08	.01	.01	.05								ASTM B23 Alloy 3
bal	7.00	.50	6.00	.08	.10	.08	.01	.01	.05								ASTM B23 Alloy 11

COMPOSITION, %																		
Zr	Hf	Sn	Cr	Fe	—	—	—	—	—	—	—	—	—	—	—	Other	MATERIAL DESIGNATION
45. ZIRCONIUM ALLOYS, WROUGHT																		
99.50	*	—	—	—														
99.20	*	—	.20	†													Zr-0 001%Hf (Grade 21)	
bal	—	1.45	.10	.14													Zr-2%Hf (Grade 11)	
bal	—	1.45	.10	.21													Zircaloy 2 (Grade 32)	
																	Zircaloy 4 (Grade 34)	

*Included with zirconium.
†Included with chromium

COMPOSITION,																	
Al	Cu	Mg	Sn	Si	Pb	—	—	—	—	—	—	—	—	—	—	Other	MATERIAL DESIGNATION
47. POWDER METAL ALLOYS — Aluminum Alloys																	
bal	.25	1.00	—	.60	—												A1-1Mg-0.6Si-0 25cu
bal	—	.60	—	.40	—												Al-0.6Mg-0 4Si
bal	4 40	.40	—	.80	—												Al-4 4Cu-0 8Si-0.4Mg
90.50	4.00	—	5 00	—	—												90.5Al-5Sn-4Cu
88.00	3.00	—	5.00	—	4.00												88Al-5Sn-4Pb-3Cu

COMPOSITION, %																	
Fe	C	Cu	Ni	Cr	Mn	Si	P	S	—	—	—	—	—	—	—	Other	MATERIAL DESIGNATION
47. POWDER METAL ALLOYS — Irons																	
97.70	.30	—	—	—	—	—	—	—								2.00 max	F-0000-N
97.70	.30	—	—	—	—	—	—	—								2 00 max.	F-0000-P
97.70	.30	—	—	—	—	—	—	—								2 00 max.	F-0000-R
97.70	.30	—	—	—	—	—	—	—								2.00 max.	F-0000-S
97.70	.30	—	—	—	—	—	—	—								2.00 max	F-0000-T

COMPOSITION, %										MATERIAL DESIGNATION
Fe	C	Cu	Ni	Cr	Mn	Si	P	S	Other	
47. POWDER METAL ALLOYS — Steels										
97.00	.80	—	—	—	—	—	—	—	2.00 max.	F-0008-P
97.00	.80	—	—	—	—	—	—	—	2.00 max.	F-0008-S
97.50	.50	—	—	—	—	—	—	—	2 00 max.	F-0005-S
95.00	.50	2.50	—	—	—	—	—	—	2.00 max.	FC-0205-S
94.50	.80	2.70	—	—	—	—	—	—	2.00 max.	FC-0208-P
94.50	.80	2.70	—	—	—	—	—	—	2.00 max.	FC-0208-S
93.20	.80	5 00	—	—	—	—	—	—	2.00 max.	FC-0508-P
89.00	.20	10.00	—	—	—	—	—	—	2.00 max.	FC-1000-N
95.00	.50	1.50	2.00	—	—	—	—	—	2.00 max.	FN-0205-S
95.00	.50	1.50	2.00	—	—	—	—	—	2.00 max.	FN-0205-T
93.00	.50	1.00	4.50	—	—	—	—	—	2 00 max.	FN-0405-R
93.00	.50	1.00	4.50	—	—	—	—	—	2.00 max.	FN-0405-S
93.00	.50	1.00	4.50	—	—	—	—	—	2 00 max.	FN-0405-T
85.00	.50	11.50	—	—	—	—	—	—	4.00 max.	FX-1005-T
78.00	.50	20.00	—	—	—	—	—	—	4.00 max.	FX-2008-T
47. POWDER METAL ALLOYS — Stainless Steels										
bal	.08	—	9.00	19 00	2.00	1.00	.04	.03		SS-304-R
bal	.08	—	12.00	17.00	2.00	1.00	.04	.03	2.50Mo	SS-316-R
bal	.15	—	—	12.50	1.00	1.00	.04	.03		SS-410-R
bal	.15	—	9.00	18.00	2.00	1.00	.20	.15	.50Mo	SS-303-R

COMPOSITION, %						MATERIAL DESIGNATION
W	C	Mo	Ag	Cu	Other	
47. POWDER METAL ALLOYS — Refractory Metal Base						
—	—	61.00	39.00	—		61Mo-39Ag
—	—	50.00	50.00	—		50Mo-50Ag

COMPOSITION, %																	MATERIAL DESIGNATION
W	C	Mo	Ag	Cu	—	—	—	—	—	—	—	—	—	—	—	Other	
47. POWDER METAL ALLOYS — Refractory Metal Base (continued)																	
50.00	*	—	50.00	—													50W + C-50Ag
51.00	—	—	49.00	—													51W-49Ag
55.00	—	—	—	45.00													55W-45Cu
56.00	*	—	—	44.00													56W + C-44Cu
65.00	—	—	35.00	—													65W-35Ag
72.50	—	—	27.50	—													72.5W-27.5Ag
74.00	—	—	—	26.00													74W-26Cu
85.00	—	—	15.00	—													85W-15Ag
87.00	—	—	—	13.00													87W-13Cu

*Included with tungsten.

COMPOSITION, %																	MATERIAL DESIGNATION
Cu	Zn	Sn	Pb	Ni	Fe	C	Al	—	—	—	—	—	—	—	—	Other	
47. POWDER METAL ALLOYS — Brasses																	
78.00	20.00	.10	1.60	—	.30	—	—										CZP-0218-T
78.00	20.00	.10	1.60	—	.30	—	—										CZP-0218-U
78.00	20.00	.10	1.60	—	.30	—	—										CZP-0218-W
90.00	10.00	—	—	—	—	—	—										90Cu-10Zn
90.00	10.00	—	.50	—	—	—	—										90Cu-10Zn-0.5Pb
70.00	30.00	—	—	—	—	—	—										70Cu-30Zn
68.50	30.00	—	1.50	—	—	—	—										68.5Cu-30Zn-1.5Pb
47. POWDER METAL ALLOYS — Bronzes																	
88.00	—	10.00	—	—	.50	1.50	—										CT-0010-N
88.00	—	10.00	—	—	.50	1.50	—										CT-0010-R
88.00	—	10.00	—	—	50	1.50	—										CT-0010-S
95.00	—	—	—	—	—	—	5.00										95Cu-5Al
77.00	—	7.00	15.00	—	1.00	1.00	—										77Cu-15Pb-7Sn-1Fe-1C

COMPOSITION, %																	MATERIAL DESIGNATION
Cu	Zn	Sn	Pb	Ni	Fe	C	Al	—	—	—	—	—	—	—	—	Other	
47. POWDER METAL ALLOYS — Copper-Nickel Alloys																	
64.00	18.00	—	—	18.00	—	—	—										CZN-1818-T
64.00	18.00	—	—	18.00	—	—	—										CZN-1818-U
64.00	18.00	—	—	18.00	—	—	—										CZN-1818-W
64.00	16.50	—	1.50	18.00	—	—	—										CZNP-1618-U
64.00	16.50	—	1.50	18.00	—	—	—										CZNP-1618-W
90.00	—	—	—	10.00	—	—	—										90Cu-10Ni
62.00	18.00	2.00	—	18.00	—	—	—										62Cu-18Ni-18Zn-2Sn
47. POWDER METAL ALLOYS — Nickel Alloys																	
30.00	—	—	—	67.00	3.00	—	—										67Ni-30Cu-3Fe

COMPOSITION, %																	MATERIAL DESIGNATION
Fe	Al	Ni	Co	Mo	Ti	Si	Mn	C	P	Cb	Cu	—	—	—	—	Other	
50. FREE MACHINING MAGNETIC ALLOYS																	
bal	—	—	—	—	—	2.50	.40	.05	.12	—	—						Magnetic Core Iron-FM
bal	—	49.00	—	—	—	.35	.50	.05	—	—	—						Hi Perm 49-FM
51. MAGNETIC ALLOYS																	
bal	—	—	—	—	—	4.00	.15	.05	—	—	—						Magnetic Core Iron
bal	—	49.00	—	—	—	.35	.50	.05	—	—	—						Hi Perm 49
bal	—	80.00	—	4.20	—	.35	.50	.02	—	—	—						HyMu 80
bal	6.00	18.00	35.00	—	8.00	—	—	—	—	—	—						Alnico XII
bal	7.80	13.50	25.00	—	—	—	—	—	—	.80	3.00						Columax-5
bal	8.00	14.00	24.00	—	—	—	—	—	—	—	3.00						Alnico V-7
bal	8.00	14.00	24.00	—	—	—	—	—	—	—	3.00						Hyflux Alnico V-7

COMPOSITION, %																	
Fe	Al	Ni	Co	Mo	Ti	Si	Mn	C	P	Cb	Cu	—	—	—	—	Other	MATERIAL DESIGNATION
51. MAGNETIC ALLOYS (continued)																	
bal	8.00	14.00	24.00	—	1.00	—	—	—	—	—	3 00						Alnico V
bal	10.00	17.00	2.50	—	—	—	—	—	—	—	—						Alnico II
bal	12.00	20.00	5.00	—	—	—	—	—	—	—	—						Alnico I
bal	12 00	25.00	—	—	—	—	—	—	—	—	6.00						Alnico III
bal	12.00	28.00	5.00	—	—	—	—	—	—	—	—						Alnico IV

COMPOSITION, %																	
Fe	Ni	Co	C	Mn	Si	—	—	—	—	—	—	—	—	—	—	Other	MATERIAL DESIGNATION
52. FREE MACHINING CONTROLLED EXPANSION ALLOYS																	
bal	36.00	—	.12	.35	.30												Invar 36
53. CONTROLLED EXPANSION ALLOYS																	
bal	35.00	—	.12	.50	.50												Invar
bal	29.00	17.00	.02	.30	.20												Kovar

SECTION 27

GLOSSARY

PRECEDING PAGE BLANK-NOT FILMED

GLOSSARY 27

Abrasive Belt Grinding: Removal of material from a workpiece, roughing and/or finishing, with a power-driven, abrasive-coated belt.

Abrasive Belt Polishing: Finishing a workpiece with a power-driven, abrasive-coated belt in order to develop a very good finish.

Abrasive Cutoff: Severing a workpiece by means of a thin, abrasive wheel

Abrasive Flow Machining: See section 10.1.

Abrasive Jet Machining: See section 10.2.

Abrasive Machining: Used to accomplish heavy stock removal at high rates by use of a free-cutting grinding wheel.

ACI: Alloy Casting Institute, as in ACI Grade CB-7Cu Cast Stainless Steel.

Acicular: Refers to alloyed cast irons which develop high strength on cooling and which have a needlelike microstructure containing martensite mixed with other microconstituents.

Active Oil: An oil which contains chemically active ingredients to prevent metal-to-metal friction (by boundary lubrication) when the pressures become too great for the natural film strength of the oil.

Aged: A heat treatment of a previously solution heat treated alloy at temperatures which permit solid state precipitation to occur. (This treatment usually develops an increase in the hardness and strength of an alloy but may decrease machinability.)

AISI: American Iron and Steel Institute. Issues general classification standards for irons and steels

Alloy Steels: Steels with carbon from 0.1 to 1.1 percent and containing alloying elements such as nickel, chromium, molybdenum, and vanadium. (The total of all such alloying elements in these type steels is usually less than 5 percent.)

Alpha-Beta Titanium Alloys: See *Titanium Alloys.*

Alpha Titanium Alloys: See *Titanium Alloys.*

AMS: Aerospace Material Specification published by the Society of Automotive Engineers (SAE), as in AMS 4803A.

Annealed: A heat treatment of an alloy above its critical or recrystallization temperature, usually followed by furnace cooling. (The treatment results in low hardness, high ductility, and usually improves tool life.)

Arc Cast: The as-cast condition produced by melting an alloy with an electrical arc.

As Cast: See *Cast.*

ASTM: American Society for Testing and Materials, as in standards such as ASTM A27, A148, etc.

Austempering: Quenching a ferrous alloy from a temperature above the transformation range, in a medium having a rate of heat abstraction fast enough to prevent the formation of high-temperature transformation products, and then holding the alloy, until transformation is complete, at a temperature below that of pearlite formation and above that of martensite formation.

Austenite: A solid solution of one or more elements in face-centered-cubic iron. (In most alloy steels, austenite is stable at heat treating temperatures and changes to other constituents such as pearlite, ferrite, martensite, etc. In the austenitic stainless steels, it is stable at room temperature as a result of alloying.)

Austenitic: Of or pertaining to *Austenite.*

B: See *Boron Steels.*

Beta Titanium Alloys: See *Titanium Alloys.*

Bhn: See *Brinell Hardness.*

Boring: Enlarging a hole by removing metal with a single- or occasionally a multiple-point cutting tool moving parallel to the axis of rotation of the work or tool.

Single-Point Boring: Cutting with a single-point tool.

Precision Boring: Cutting to tolerances held within narrow limits.

Gun Boring: Cutting of deep holes.

Jig Boring: Cutting of high-precision and accurate-location holes.

Groove Boring: Cutting accurate recesses in hole walls.

Boron Steels: Steels with boron additions in amounts of 0.0005 to 0.003 percent to increase hardenability, as in 86B45, 94B30, etc.

Boundary Lubrication: Lubrication by a solid lubricant (a material which has relatively low shear strength). This lubricant may be introduced in solid form, or it may be formed on fresh metal surfaces by chemical reaction.

Brinell Hardness: A test for determining the hardness of a material by forcing a hard steel or carbide ball of specified diameter into it under a specified load. (The result is expressed as the Brinell hardness number, which is the value obtained by dividing the applied load in kilograms by the surface area of the resulting impression in square millimeters.)

Broaching: Cutting with a tool which consists of a bar having a single edge of a series of cutting edges (that is, teeth) on its surface. The cutting edges of multiple-tooth or

successive, single-tooth broaches increase in size and/or change in shape. The broach cuts in a straight line or axial direction when relative motion is produced in relation to the workpiece, which may also be rotating. The entire cut is made in single or multiple passes over the workpiece to shape the required surface contour.

Pull Broaching: Tool pulled through or over workpiece.

Push Broaching: Tool pushed over or through workpiece.

Chain Broaching: A continuous, high-production surface broach.

Tunnel Broaching: Work travels through an enclosed area containing broach inserts.

BUE: See *Built-up Edge.*

Buffing: A two-stage operation: 1) cutting down and 2) coloring. Cutting down removes scratch marks from rough polishing, stretch marks from forming, die marks or other surface imperfections It makes a relatively smooth surface smoother. Coloring refines the cut-down surface and brings out maximum luster.

Built-up Edge (BUE): A piece of work material which has been strain hardened and pressure welded to the cutting edge of a tool or to the surface of a workpiece.

Burnishing: Finish sizing and smooth finishing of surfaces (previously machined or ground) by displacement, rather than removal, of minute surface irregularities with smooth, point-of-line contact, fixed or rotating tools.

Carbides: A compound of carbon with one or more metallic elements Often refers to one of the general class of pressed and sintered cutting tools which contain tungsten carbide plus smaller amounts of titanium and tantalum carbides along with cobalt which acts as a binder. (It is also used to describe hard compounds in steels and cast irons.)

Carbon Steels: Steels with carbon plus small amounts of manganese, silicon, sulfur, phosphorus, or other elements.

Carburized: A condition attained by using carburizing heat treatments to increase the carbon content at the surface of steels. (This is done by placing the parts in contact with carbonaceous solids, liquids, or gases at approximately 1600° to 1700°F (870° to 927°C). The depth of penetration and amount of carbon pickup are a function of the time, temperature and carburizing medium. Hardening treatments of carburized surfaces develop hardnesses up to 65 R_C.)

Case Hardening: A heat treating method by which the surface layer of alloys is made substantially harder than the interior. (Carburizing and nitriding are common ways of case hardening steels.)

Cast: A state of the alloy after solidification of the molten alloy.

Cast Steels: Steels which are cast to shape and used without having been hot rolled or forged but which are usually heat treated to produce appropriate material properties

Cemented Carbides: Carbides that are mixed with cobalt metal powder, milled in ball mills and then pressed into desired shapes and sintered. (Used primarily for cutting tools, wire-drawing dies and parts subject to heavy abrasive wear.)

Ceramics: The general class of hard, brittle, and high-melting nonmetallic materials such as aluminum oxide, zirconium oxide, and beryllium oxide. (This same term also is used to designate aluminum oxide and other similar type ceramic cutting tools.)

Chatter Marks: Imperfections on the work surface usually caused by vibrations of the tool and/or workpiece.

Chemical Coolant: A cutting fluid which does not contain any mineral oil; usually a true solution in water or a fine colloidal solution.

Chemical Machining: See section 13.1.

Chlorine: A common extreme pressure (EP) additive used to promote lubrication.

Cold Drawn: A condition produced by reducing hot rolled rod to size by pulling the rod through a die of the desired diameter. (This is frequently done at room temperature but, in any event, must be carried out below the recrystallization temperature of the material. This process often improves machinability by providing better surface finish and chip control.)

Cold Form Tapping: Producing internal threads by displacing material rather than removing it as either the tap or the workpiece is rotated. The thread form is produced by a tool, which has neither flutes nor cutting edges. The tool resembles a simple screw when viewed from the side, but the end view shows that both the major and minor diameters have irregular contours for displacing the work material.

Cold Rolled: An alloy condition developed by reducing hot rolled stock by passing it between rolls to the desired thickness. Temperature limitations are the same as for cold drawing.

Compacted Graphite Cast Irons: Class of cast irons characterized by graphite that is interconnected within eutectic cells, as is the flake graphite in gray iron, but is coarser and more rounded. (Well suited for applications where neither gray iron nor ductile iron is completely satisfactory.)

Controlled Expansion Alloys: Special group of iron alloys with low thermal expansion coefficients recommended for applications that require very low dimensional changes with variations in temperature.

Coolant: Liquid used to cool the work and tool and to prevent rusting or corrosion. See also *Cutting Fluid.*

Corrosion Resistant Steels: A term often used to describe the cast stainless steels and to differentiate those cast steels used primarily for corrosion applications.

Counterboring: Removal of material to enlarge a hole for part of its depth with a rotary, pilot-guided, end-cutting tool having two or more cutting lips and usually having straight or helical flutes for the passage of chips and the admission of a cutting fluid.

Countersinking: Beveling or tapering the work material around the periphery of a hole creating a concentric surface at an angle less than 90° with the centerline of the hole for the purpose of chamfering holes or recessing screw and rivet heads

Coupling Agent: A mutual solvent; an emulsifier.

Creaming: A concentrating of oil droplets of an emulsion near the surface when the emulsion stands quiescent for a sufficient period of time.

Cutting Fluid: Fluid (liquid, gas, or mist) applied to the working part of a tool or cutter to promote more efficient machining. See also *Coolant*.

Cutting Oil: A cutting fluid used where lubrication is the prime consideration and the cooling factor is of less importance.

Deburring: Removal of burrs, sharp edges or fins from parts by filing, grinding or tumbling the work in a barrel with abrasives suspended in a suitable liquid medium. Sometimes called "burring."

Die Cast: Alloy condition resulting from casting in metallic dies.

Drawing: A term often used to mean the same as tempering, which is the preferred designation. ("Drawing" should be reserved for hot and cold mechanical working operations.)

Drilling: Hole making with a rotary, end-cutting tool having one or more cutting lips and one or more helical or straight flutes or tubes for the ejection of chips and the passage of a cutting fluid.

Center Drilling: Drilling a conical hole in the end of workpiece.

Core Drilling: Enlarging a hole with a chamfer-edged, multiple-flute drill.

Spade Drilling: Drilling with a flat blade drill tip.

Step Drilling: Using a multiple-diameter drill.

Gun Drilling: Drilling a deep hole using special straight-flute drills (often with a single lip) and cutting fluid at high pressures.

Oil-Hole or Pressurized-Coolant Drilling: Using a drill with one or more continuous holes through its body and shank to permit the passage of a high-pressure cutting fluid which emerges at the drill point and ejects chips.

Ductile Cast Irons: Irons made by inoculating liquid iron from a cupola with magnesium-nickel or other inoculants to produce graphite in a nodular form. (These cast irons are sometimes called "nodular irons.")

Electrical Discharge Grinding: See section 12.2.

Electrical Discharge Machining: See section 12.3.

Electrical Discharge Sawing: See section 12.4.

Electrical Discharge Wire Cutting: See section 12.5.

Electrochemical Deburring: See section 11.1.

Electrochemical Discharge Machining: See section 11.2.

Electrochemical Grinding: See section 11.3.

Electrochemical Honing: See section 11.4.

Electrochemical Machining: See section 11.5.

Electrochemical Polishing: See section 11.6.

Electrochemical Sharpening: See section 11.7.

Electrochemical Turning: See section 11.8.

Electron Beam Machining: See section 12.1.

Electropolishing: See section 13.2.

Electro-stream™: See section 11.9.

Emulsifiable Oil: A straight oil or blend which contains an emulsifier or coupling agent so it will form a stable emulsion in water.

Emulsion: An oily mass in suspension in a watery liquid or vice versa.

EP Additive: See *Extreme Pressure Additive.*

EPA: United States Environmental Protection Agency.

Extreme Pressure Additive: A compound which reacts with the surface of the metal (or tool) to form thin films of metallic compounds (usually, a chloride, sulfide, or phosphate) which have relatively low shear-strength.

Extruded: Wrought material produced by forcing an alloy or other material through a die.

Fatty Acid: Any of the series of saturated or unsaturated acids ($C_nH_{2n}O_2$) such as stearic, oleic, and palmitic acids which occur in natural fats and natural oils.

Fatty Oils: Organic oils: the most common are lard oil and sperm oil.

Ferrite: A solid solution of one or more elements in body-centered-cubic iron. (Ferritic microstructure is commonly found in steels and cast irons and generally allows for good tool life.)

Ferritic: Of or pertaining to *Ferrite.*

Filled Plastics: Plastics containing a relatively inert material that has been added to modify strength, permanence, working properties, or other qualities, or to lower cost.

Flame Hardened: Surface hardened by controlled torch heating followed by quenching with water or air.

Flame (Thermal) Sprayed Materials: Hard, wear resistant materials deposited as coatings on the surfaces of metals by a blast-gas-stream-ignited mixture of oxygen and acetylene.

Forged: A cold or hot mechanical working process performed by presses or hammers to shape metals. (Treatments such as annealing or normalizing should generally be applied after forging to improve machinability.)

Gear Cutting: Producing tooth profiles of equal spacing on the periphery, internal surface, or face of a workpiece by means of an alternate shear gear-form cutter or a gear generator.

Gear Hobbing: Gear cutting by use of a tool resembling a worm gear in appearance, having helically spaced cutting teeth. In a single-thread hob, the rows of teeth advance exactly one pitch as the hob makes one revolution. With only one hob, it is possible to cut interchangeable gears of a given pitch of any number of teeth within the range of the hobbing machine.

Gear Milling: Gear cutting with a milling cutter that has been formed to the shape of the tooth space to be cut. The tooth spaces are machined one at a time.

Gear Shaping: Gear cutting with a reciprocating gear-shaped cutter rotating in mesh with the work blank.

Gear Shaving: A finishing operation performed with a serrated rack or gear-like cutter in mesh with the gear, but with their axis skewed.

Germicide: Any agent which destroys germs or micro-organisms.

Glasses: Inorganic products of fusion which have cooled to a rigid condition without crystallizing. Typically hard and relatively brittle.

Gray Cast Irons: Alloys primarily of iron, carbon, and silicon along with other alloying elements in which the graphite is in flake form. (These irons are characterized by low ductility but have many other desirable properties, such as good castability and good damping capacity.)

Grinding: Material removal by use of abrasive grains held by a binder.

Surface Grinding: Producing a flat surface with a rotating grinding wheel as the workpiece passes under the wheel.

Cylindrical Grinding: Grinding the outside diameters of cylindrical workpieces held between centers.

Internal Grinding: Grinding the inside of a rotating workpiece by use of a wheel spindle which rotates and reciprocates through the length of depth of the hole being ground.

Centerless Grinding: Grinding cylindrical surfaces without use of fixed centers to rotate the work. The work is supported and rotates between three fundamental machine components: the grinding wheel, the regulating wheel, and the work guide blade.

Gear Grinding: Removal of material to obtain correct gear tooth form by grinding. This is one of the more exact methods of finishing gears.

Thread Grinding: Thread cutting by use of a suitably formed grinding wheel.

H: A letter listed along with the composition of aluminum and magnesium alloys indicating that the alloy has been cold worked. (H12, H14, etc., are used to indicate various degrees of cold working.)

Halogen: The group of elements: chlorine, fluorine, bromine, and iodine.

Hardened: Designates condition produced by various heat treatments, such as quench hardening, age hardening, and precipitation hardening.

Hardness: The relative ability of a material to resist indentation.

Heat Resistant Steels: Cast steels which are highly alloyed and used for high temperature applications such as furnace conveyor parts, etc.

Heat Treatment: Heating and cooling of metal or an alloy in the solid state for the purpose of obtaining certain desirable conditions or properties.

High Speed Steels: Tool steels which contain tungsten, molybdenum, vanadium, cobalt, carbon, and other elements.

High Strength Steels: Class of steels capable of heat treatment to develop yield strengths of 200,000 psi [138 MPa] or higher. (Originally developed to obtain improved strength-to-weight ratios in materials for transportation equipment.)

High Temperature Alloys: Generally alloys of nickel, cobalt, or iron which are used at temperatures in excess of

1200°F [650°C] in applications such as rockets, jet engine blades, and compressor and turbine discs, etc.

Hollow Milling: Using a special end-cutting mill so designed to leave a core after feeding into or through the workpiece.

Honing: A finishing operation using fine grit abrasive stones to produce accurate dimensions and excellent finish.

Hot Machining: Machining in which the workpiece shear zone is heated by auxiliary means to reduce the shear strength and increase the machinability of the material.

Hot Rolled: A term used to describe alloys which are rolled at temperatures above the recrystallization temperature. (Many alloys are hot rolled, and machinability of such alloys may vary because cooling conditions differ from lot to lot.)

Hydrodynamic Lubrication: Lubrication where the viscosity of the lubricant keeps the surfaces separated by a fluid film.

Hydrodynamic Machining: See section 10.3.

Induction Hardened: Surface or through hardened using induction heating followed by quenching with water or air.

Inverted Emulsion: A dispersion of droplets of water in oil which is produced when a small quantity of water is mixed with a relatively large quantity of oil.

ISO: International Organization for Standardization. International standardizing body comprising the national standardizing bodies of several countries.

Knoop Hardness: Microhardness measured using a diamond indenter ground to pyramidal form and expressed as the ratio of the load applied to the indenter (kilograms) to the unrecovered projected area (mm^2).

L: See *Leaded Alloys.*

Lapping: A finishing operation using fine abrasive grits loaded into a lapping material such as cast iron. Lapping provides major refinements in the workpiece including: 1) extreme accuracy of dimension, 2) correction of minor imperfections of shape, 3) refinement of surface finish, and 4) close fit between mating surfaces.

Laser Beam Machining: See section 12.6.

Laser Beam Torch: See section 12.7.

Leaded Alloys: Alloys to which lead has been added to improve machinability, as in 41L30, 86L20, etc.

Low Stress Grinding: See section 10.4.

Machinability: The relative difficulty of a machining operation with regard to tool life, surface roughness, and power consumption.

Machinable Carbides: Carbide grains in a steel matrix readily machinable in the annealed state and hardenable by heat treatment to 64 to 70 R_C.

Magnetic Alloys: Alloys composed primarily or totally of nonferrous metals that can be used for making permanent magnets.

Malleable Cast Irons: Irons made by malleablizing white cast iron. See also *Malleablizing.*

Malleablizing: Process of annealing brittle white cast iron in such a way that the combined carbon is wholly or partly transformed to graphitic or temper-carbon nodules in a ferritic or pearlitic microstructure, thus providing a ductile and machinable material.

Maraged: Describes a series of heat treatments used to treat high strength steels of complex composition (maraging steels) by aging of martensite.

Maraging Steels: Special class of steels that are hardened by the precipitation of intermetallic compounds at temperatures of about 900°F [480°C].

Martensite: An acicular or needlelike microstructure that is formed in quenched steels. (It is very hard and brittle in the as-quenched form and therefore is usually tempered before being placed into service. The harder forms of tempered martensite have poor machinability.)

Martensitic: Of or pertaining to *Martensite.*

Metal Slitting: An operation using a thin circular saw blade to produce a narrow slit in the workpiece. The workpiece is fed into the saw usually on a setup similar to peripheral milling.

Metallic Soap: Any oil of mineral origin, such as petroleum.

Milling: Using a rotary tool with one or more teeth which engage the workpiece and remove material as the workpiece moves past the rotating cutter.

Face Milling: Milling a surface perpendicular to the axis of the cutter. Peripheral cutting edges remove the bulk of the material while the face cutting edges generate the workpiece finish.

End Milling: Milling accomplished with a tool having cutting edges on its cylindrical surfaces as well as on its end. In peripheral end milling, the peripheral cutting edges on the cylindrical surface are used; while in end milling-slotting, both end and peripheral cutting edges remove metal.

Side and Slot Milling: Milling of the side or slot of a workpiece using a peripheral cutter.

Slab Milling: Milling of a surface parallel to the axis

of a helical, multiple-toothed cutter mounted on an arbor.

Straddle Milling: Peripheral milling a workpiece on both sides at once using two cutters spaced as required.

Miscible: Capable of being mixed.

NIOSH: United States National Institute for Occupational Safety and Health.

Nitrided: Surface hardened by absorption of nitrogen from a gaseous or salt bath medium.

Nitriding: A heat treating method in which nitrogen is diffused into the surface of a solid ferrous alloy. (This is done by heating the metal at a temperature of about 950°F [510°C] in contact with ammonia gas or other suitable nitrogenous materials. Because nitrides form, the surface becomes much harder than the interior. Depth of the nitrided surface is a function of the length of time of exposure and can vary from 0.0005- to 0.032-inch [0.013 to 0.81 mm] thick. Hardness is generally 65 to 70 R_C; consequently, these structures are almost always ground.)

Nitriding Steels: Steels which are selected because they form good case hardened structures during the nitriding process. (In these steels, elements such as aluminum and chromium are important for producing a good case.)

Nodular Cast Irons: See *Ductile Cast Irons.*

Normalized: Heat treatment of ferrous alloys above the transformation range, followed by cooling in still air to a temperature below the transformation range. (This is often done to refine or homogenize the grain structure of castings, forgings, and wrought steel products.)

O: A letter often listed along with the composition of aluminum and magnesium alloys indicating that the alloy has been annealed.

OSHA: United States Occupational Safety and Health Administration.

Pearlite: A microconstituent found in iron-base alloys consisting of a lamellar (platelike) composite of ferrite and iron carbide. (This structure results from the decomposition of austenite and is very common in cast irons and annealed steels.)

Pearlitic: Of or pertaining to *Pearlite.*

Permanent Mold: A mold, usually made of metal, which is used repeatedly for the production of a number of castings of the same form.

PH: Letters used with the composition of precipitation hardening stainless steels to designate that special heat treatments using in part a refrigeration cycle have been performed on the material to develop specific properties.

Photochemical Machining: See section 13.3.

Planing: Producing flat surfaces by linear reciprocal motion of the work and the table to which it is attached relative to a stationary, single-point cutting tool.

Plasma Beam Machining: See section 12.8.

Plastics: Materials that contain as an essential ingredient an organic substance of large molecular weight, are solid in the finished state, and can be shaped by flow at some stage in their manufacture or processing into finished articles.

Plated Materials: Metals applied in thin films to the surface of a material by dipping or by electrodeposition.

P/M: See *Powder Metallurgy.*

Polishing: Removal of metal by the action of abrasive grains carried to the work by a flexible support, generally either a wheel or a coated abrasive belt.

Powder Metal Alloys: Alloyed metal powders that have been pressed or rolled into compacts that are sintered to produce shaped components or bar stock.

Powder Metallurgy: A process involving pressing of powdered metal followed by heating (sintering) to produce bearings, friction materials, refractory alloys, etc.

Precipitation Hardening Stainless Steels: Certain stainless steel compositions which respond to precipitation hardening or aging treatment.

Pressed (with reference to *Powder Metallurgy*): The "as pressed" condition of alloys when compacted from powders. (Pressing of powdered metals is generally followed by sintering. Some difficult- or impossible-to-machine materials such as tungsten and carbides are shaped by various machining operations in the "green" condition, generally produced by low temperature presintering.)

Quenched: Rapid cooling of alloys by immersion in liquids or gases after heating.

Reaming: An operation in which a previously formed hole is sized and contoured accurately by using a rotary cutting tool (reamer) with one or more cutting elements (teeth). The principal support for the reamer during the cutting action is obtained from the workpiece.

Form Reaming: Reaming to a contour shape.

Taper Reaming: Using a special reamer for taper pins.

Hand Reaming: Using a long lead reamer which permits reaming by hand.

Pressure-Coolant Reaming (or Gun Reaming): Using a multiple-lip, end-cutting tool through which coolant is forced at high pressure to flush chips

ahead of the tool or back through the flutes for finishing of deep holes.

Refractory Alloys: Alloys or elements which have melting temperatures above 4000°F (2200°C). (The most common refractory alloys of current industrial interest are tungsten, molybdenum, columbium, and tantalum.)

Resulfurized Alloys: Alloys which have sulfur added to improve machinability.

Rockwell Hardness: A measure of the difference in depth of penetration of an indenter between a major and a minor load. (Normally a minor load of 10 kilograms is applied, followed by the application and release of a major load which will vary from 60 to 150 kilograms. The more commonly used Rockwell scales are Rockwell "C" (R_C), using a diamond sphero-conical penetrator and a 150 kilogram major load, and Rockwell "B" (R_B), using a 1/16 inch diameter steel ball penetrator and a major load of 100 kilograms. Other scales used in this data book are R_A, R_E, R_F, R_H, R_M, and R_R.

Rolled: See *Cold Rolled, Hot Rolled.*

Rotary Filing and Burring: Machining or smoothing surfaces with contour-fitting rotary tools where only a minimum amount of material is to be removed.

Routing: Cutting out and contouring edges of various shapes in a relatively thin material using a small diameter rotating cutter which is operated at fairly high speeds.

rpm: Revolutions per minute.

Sawing: Using a toothed blade or disc to sever parts or cut contours.

Circular Sawing: Using a circular saw fed into the work by motion of either the workpiece or the blade.

Power Band Sawing: Using a long, multiple-tooth continuous band resulting in a uniform cutting action as the workpiece is fed into the saw.

Power Hack Sawing: Sawing in which a reciprocating saw blade is fed into the workpiece.

SAE: Society of Automotive Engineers, as in SAE G1800.

Sand Casting: Non-precision process for producing castings using molds made from natural or synthetic sand.

Shaped Tube Electrolytic Machining: See section 11.10.

Shaping: Using single-point tools fixed to a ram reciprocated in a linear motion past the work.

Form Shaping: Shaping with a tool ground to provide a specified shape.

Contour Shaping: Shaping of an irregular surface, usually with the aid of a tracing mechanism.

Internal Shaping: Shaping of internal forms such as keyways and guides.

Shore Hardness (A and D): Indentation hardness measured using a durometer having an indenter formed from hardened steel rod. (Type A durometers measure softer materials, while Type D durometers are used for harder materials.)

Sintered: The sintered condition results from a heating of pressed powdered materials for specified times at elevated temperature. Improved strength and other benefits result, but generally machinability is decreased.

Skiving: Generating cylindrical forms by moving a form tool laterally through a rotating workpiece.

Snagging: Heavy stock removal of superfluous material from a workpiece by using a portable or swing grinder mounted with a coarse grain abrasive wheel.

Soluble Oil: See *Emulsifiable Oil.*

Solution Treated: A process by which it is possible to dissolve microconstituents by taking certain alloys to an elevated temperature and then keeping them in solution after quenching. (Often a solution treatment is followed by a precipitation or aging treatment to improve the mechanical properties. Most high temperature alloys which are solution treated and aged machine better in the solution treated state just before they are aged.)

Spotfacing: Using a rotary, hole-piloted end-facing tool to produce a flat surface normal to the axis of rotation of the tool on or slightly below the workpiece surface.

Spray Lubrication: Describes the application of a lubricant by means of spraying equipment in much the same manner as paint is sprayed.

ST: See *Solution Treated.*

STA: Solution treated and aged. See *Solution Treated* and *Aged.*

Stainless Steels: Steels which have good or excellent corrosion resistance. There are three broad classes of stainless steels—ferritic, austenitic, and martensitic. These various classes are produced through the use of various alloying elements in differing quantities.

Strain Hardening: See *Work Hardening.*

Stress Corrosion: Corrosion facilitated by high residual surface stress imposed by machining or grinding operations.

Stressed Relieved: The treatment used to relieve the internal stresses induced by forming or heat treating operations. (It consists of heating a part uniformly, followed by cooling slow enough so as not to reintroduce stresses. To

obtain low stress levels in steels and cast irons. temperatures as high as 1250°F [575°C] may be required.)

Structural Steels: Steels covering a wide range of strengths and used for structural purposes. These steels are sometimes called high strength steels or constructional steels. In this handbook. the term high strength steels is reserved primarily for those steels which are used at strength levels of 200,000 psi [138 MPa] or greater.

Sub-zero Machining: Using refrigerant or other means for cooling the workpiece during. or before. machining.

Sulfo-chlorinated Oil: Cutting oil containing sulfur and chlorine.

Sulfur: A common extreme pressure (EP) additive used to promote boundary lubrication.

Superfinishing: An abrasive process utilizing either a bonded stock for a cylindrical workpiece or a cup wheel for flat and spherical work. A large contact area. approximately 30 percent. exists between workpiece and abrasive. The object of superfinishing is to remove surface fragmentation and to correct inequalities in geometry. such as grinding feed marks and chatter marks.

Surface Active Agent: Materials capable of lowering surface and interfacial tensions. See *Wettability*.

Synthetic Fluids: Products which do not contain any mineral oil and usually form a true solution in water.

T: A letter often listed along with the numbers used to designate aluminum and magnesium alloys indicating that the alloy has been subjected to heat treatment. (T4. T5. T6. etc.. indicate various specific heat treatments.)

Tapping: Producing internal threads with a cylindrical cutting tool having two or more peripheral cutting elements shaped to cut threads of the desired size and form. By a combination of rotary and axial motions. the leading end of the tap cuts the thread while the tap is supported mainly by the thread it produces.

Tempered: Reheating of hardened steels or hardened cast irons to reduce hardness and to lower internal stress. (The temperature used depends upon the mechanical properties specified but generally ranges from 300° to 1200°F [150° to 650°C].)

Tempered Martensite: A two-phase microstructure containing carbide particles in a ferrite matrix which results from reheating martensite to improve toughness.

Thermally Assisted Machining: See section 10.5.

Thermochemical Machining: See section 13.4.

Thermoplastic: A plastic which can be softened repeatedly by an increase and hardened by a decrease in temperature. (Heating causes physical changes rather than chemical.)

Thermosetting Plastic: A plastic which upon heating is changed chemically into a material having new properties.

Threading: Producing external threads on a cylindrical surface.

Die Threading: A process for cutting external threads on cylindrical or tapered surfaces by the use of solid or self-opening dies.

Single-Point Threading: Turning threads on a lathe.

Thread Grinding: See definition under *Grinding*.

Thread Milling: A method of cutting screw threads with a milling cutter.

Titanium Alloys: Alloys of the element titanium. (They combine light weight. excellent strength. moderately good high temperature strength. and excellent corrosion resistance. Various alloying elements and heat treatments provide differing crystal structures. Depending upon the crystal structure of the finished alloy. they are classified as alpha. beta. or alpha-beta alloys.)

Titanium Carbide: Carbides. used as tool materials. in which the greatest amount of carbide is titanium instead of tungsten and which also contain other carbides plus nickel and molybdenum as binders.

Tool Steels: Steels used to make cutting tools and dies. Many of these steels have considerable quantities of alloying elements such as chromium. carbon. tungsten. molybdenum. and other elements. These form hard carbides which provide good wearing qualities but at the same time decrease machinability. Tool steels in the trade are classified for the most part by their applications. such as hot work die (type H). cold work die (types D. A and O). high speed (types T and M). shock resisting (type S). mold (type P). special purpose (type L). and water hardening (type W).

Total Form Machining: See section 10.6.

Tramp Oil: Leakage into the cutting fluid system from the hydraulic or the lubrication systems of machine tools.

Transformation Temperature: The temperature at which a change in phase occurs. In a metal. phase transformation occurs at a specific temperature.

Trepanning: Cutting with a boring tool so designed as to leave an unmachined core when the operation is completed.

Tumble Grinding: Various surfacing operations ranging from deburring and polishing to honing and microfinishing of metallic parts before and after electroplating.

Turning: Generating cylindrical forms by removing metal with a single-point cutting tool moving parallel to the axis of rotation of the work.

Single-Point Turning: Using a tool with one cutting edge.

Face Turning: Turning a surface perpendicular to the axis of the workpiece

Form Turning: Using a tool with a special shape.

Turning Cutoff: Severing the workpiece with a special lathe tool

Box Tool Turning: Turning the end of a workpiece with one or more cutters mounted in a box-like frame, primarily for finish cuts

Ultimate Strength: The maximum stress expressed in pounds per square inch or pascals which a material will carry before breaking under a slowly applied, continually increasing load.

Ultrasonic Machining: See section 10.7.

Water Jet Machining: See section 10.8.

Wettability: The relative ease with which a liquid spreads over a surface

Wetting Agent: An additive which reduces surface and interfacial tension and, therefore, facilitates spreading of a fluid over a surface

White Cast Iron: Hard, brittle, difficult-to-machine irons containing 2 to 6 percent carbon, the majority of which is present as iron carbides (Fe_3C) (Excellent material for certain wear- and abrasion-resistant applications.)

Work Hardening: A hardening process which may occur during cold working or machining.

Wrought: Condition of a material which has been worked mechanically as in forging, rolling, drawing, etc

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